nagra

Technical Report 09-06

The Nagra Research, Development and Demonstration (RD&D) Plan for the Disposal of Radioactive Waste in Switzerland

November 2009

National Cooperative for the Disposal of Radioactive Waste

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Summary

Nagra's mission is to develop safe geological repositories in Switzerland for all radioactive wastes arising in Switzerland. Two types of repositories are foreseen, one for low and intermediate level waste (L/ILW) and one for spent fuel, vitrified high level waste and long-lived ILW (SF/HLW/ILW). Repository implementation involves a stepwise process that takes several decades, thus a comprehensive planning base for the scientific and engineering work is needed, which is presented in the RD&D (research, development and demonstration) plan. The main objective of the RD&D Plan is to establish the purpose, scope, nature and timing of various future RD&D activities, starting from the various requirements and planning assumptions.

Chapter 1 presents the overall objectives of the report and a brief history of the steps leading to the present situation. The planning of work is conditioned by the Federal Government decision in 2006 that Nagra had successfully shown in *Project Entsorgungsnachweis* (disposal feasibility) that safe disposal of SF/HLW/ILW in Switzerland is technically feasible. Earlier studies and safety authority reviews had already in 1988 lead to the Federal Government decision on the overall feasibility of safe disposal of L/ILW. Following the *Project Entsorgungsnachweis* decision, the Federal Government initiated the Sectoral Plan for Geological Repositories, which elaborates the siting process. The Sectoral Plan provides a framework within which specific objectives must be met for selecting suitable sites for disposal of both L/ILW and SF/HLW/ILW for which general licence applications are to be made. The overall planning is based on the status as of Nagra's submission of proposals for Stage 1 of the Sectoral Plan, which should result in the selection of geologically suitable siting regions.

Chapter 2 presents the overall planning premises for implementation of repositories for L/ILW and SF/HLW/ILW including the assumed schedule, the waste types and quantities and the safety strategy for the repositories. The time plan is presented, which includes the Sectoral Plan and general licence procedure, construction and operation of Underground Research Laboratories (URLs) at the sites, construction licence procedure and the operating licence procedure. It is expected that emplacement of L/ILW could begin in about 2035, whereas SF/HLW emplacement would begin about 2050. Waste emplacement is followed by a monitoring period (planning assumption of 50 years), at the end of which an application would be made for closure. The various waste types and quantities produced by nuclear power plants and medicine, industry and research are summarised and the safety concepts for the two repositories are illustrated.

Chapter 3 discusses the RD&D planning process and methodology and the various categories of requirements that dictate the nature and timing of the programme and the planned RD&D. These include legal, regulatory and policy requirements; waste producer requirements; authorities' recommendations; public expectations; and technology and safety requirements. Together these frame the issues that must be addressed in the programme and establish the nature and timing of the various elements of technical and scientific work.

Chapter 4 summarizes the RD&D issues for SF/HLW identified by Nagra in *Project Entsorgungsnachweis* and the recommendations made in the formal reviews of the project that were requested by the Federal Government. The broad areas of work required for development of a L/ILW repository are also identified. The status of development of the various categories of technology required for repository implementation is discussed in the context of worldwide progress in the various technology development areas.

Chapter 5 elaborates the strategic requirements for developing the two types of repositories. The definition of the waste types, their properties and the legal and regulatory requirements for disposal set the framework for the timing of implementation as well as for the repository concepts needed to safely dispose of the waste. In the repository concepts long-term safety must be provided by multiple passive safety barriers with a balanced contribution from the engineered and geological systems. The repository design concepts include: i) the main facility, where wastes will be disposed of and which will be backfilled and sealed in due time after waste emplacement; ii) the test zones, where site-specific data for the safety-relevant properties of the host rock are acquired to confirm the safety and technical feasibility; iii) the pilot facility, where the behaviour of waste, backfill material and host rock is monitored until the end of the monitoring period and in which data is collected to confirm safety with a view to closure. Host rocks with favourable properties must be selected within stable large-scale geologic-tectonic situations, which ensure a significant contribution of the geological barrier to the safety functions.

The Sectoral Plan process is discussed in some detail in order to explain the requirements on Nagra's RD&D programme for each of the stages of site selection up to the general licence application. For Stage 1, the selection of geologically suitable regions, the steps are outlined that led to the proposal of the six geological siting regions for the L/ILW repository (Südranden, Zürcher Weinland, Nördlich Lägeren, Bözberg, Jura-Südfuss, Wellenberg) and the three geological siting regions for the HLW repository (Zürcher Weinland, Nördlich Lägeren, Bözberg). Stage 2 requires the selection of at least two sites for L/ILW and HLW repositories, which is followed by Stage 3, with the selection of one site for each repository, which would provide the basis for the general licence application. The specificity of the requirements of the Sectoral Plan combined with the results of the prior work programme lead to a rather clear definition of the RD&D activities and the main expected reports for each of the stages up to the general licence application.

For the subsequent stages of repository implementation, i.e. construction and operation of a rock laboratory at the chosen site, construction of the repository and operation of the repository until final closure, the broad nature of the work is defined. This permits the level of maturity of the science and technology for each stage to be identified, such that the RD&D studies are appropriately timed and resources are effectively managed.

Chapter 6 gives an overview of the RD&D work to be done in the next 5 to 10 years, i.e. the time frame up to the general licence application, including the objectives, status and principal focus in the various areas, including:

- geological investigations (compliance with requirements for properties and geometry of host rocks and confining units and for long-term geological evolution; data for key safety-relevant parameters)
- safety assessment (compliance with requirements for operational and long-term safety)
- radioactive waste and materials (compliance with requirements for waste)
- repository engineering concepts, including concepts for waste retrievability and monitoring. This includes also the concepts for the engineered barrier system and their performance (compliance with requirements for repository design).

Zusammenfassung

Die Hauptaufgabe der Nagra besteht in der Vorbereitung von sicheren geologischen Tiefenlagern in der Schweiz für alle radioaktiven Abfälle, die in der Schweiz anfallen. Es sind zwei Lager vorgesehen, eines für die schwach- und mittelaktiven Abfälle (SMA) und eines für die abgebrannten Brennelemente, die verglasten hochaktiven Abfälle und die langlebigen mittelaktiven Abfälle (BE/HAA/LMA). Die Lagerrealisierung erfolgt in einem schrittweisen Prozess, der sich über mehrere Jahrzehnte erstreckt, was eine umfassende Planung der wissenschaftlichen und technischen Arbeiten erforderlich macht; diese Planung ist im vorliegenden Forschungs-, Entwicklungs- und Demonstrations-Plan ("Research, Development & Demonstration", engl. Abkürzung RD&D) dokumentiert. Das Hauptziel des RD&D-Plans liegt in der Festlegung des Zwecks, des Umfangs, der Art und der zeitlichen Abfolge der verschiedenen zukünftigen RD&D-Aktivitäten, basierend auf den entsprechenden Anforderungen und Planungsannahmen für die Lagerrealisierung.

Kapitel 1 diskutiert die übergeordnete Zielsetzung des Berichts und gibt einen kurzen geschichtlichen Abriss der Schritte, die zur heutigen Situation geführt haben. Die Arbeitsplanung geht vom Bundesratsentscheid zum Projekt Entsorgungsnachweis aus dem Jahre 2006 aus, welcher den Nachweis der Nagra, dass die sichere Entsorgung der BE/HAA/LMA in der Schweiz technisch machbar ist, positiv beurteilt hat. Die Machbarkeit der sicheren Entsorgung der SMA wurde bereits 1988 vom Bundesrat anerkannt. Nach dem positiven Entscheid des Bundesrats zum Projekt Entsorgungsnachweis hat der Bundesrat im April 2008 den Sachplan geologische Tiefenlager genehmigt, in dessen Rahmen die Standortwahl erfolgt. Der Sachplan legt im Konzeptteil die Sachziele des Bundes sowie das Verfahren fest, wie die Auswahl geeigneter Standorte für BE/HAA/LMA und SMA zu erfolgen hat, für die später Rahmenbewilligungsgesuche einzureichen sind. Als Planungsgrundlage für vorliegenden RD+D-Plan dienen die eingereichten Vorschläge der Nagra für Etappe 1 des Sachplans, die zur Auswahl von geeigneten geologischen Standortgebieten führen wird.

Kapitel 2 enthält die übergeordneten Planungsannahmen für die Realisierung der Tiefenlager für SMA und BE/HAA/LMA, einschliesslich des angenommenen Zeitplans, der Art und Menge der Abfälle sowie der Sicherheitsstrategie für die Tiefenlager. Der Zeitplan umfasst das Sachplanverfahren und das Rahmenbewilligungsverfahren, den Bau und Betrieb der untertägigen Felslabors an den Standorten, das nukleare Bau- und das Betriebsbewilligungsverfahren. Es wird erwartet, dass der Betrieb des SMA-Lagers ungefähr im Jahr 2035 und derjenige des Lagers für die BE/HAA/LMA ungefähr im Jahr 2050 beginnt. Nach der Abfalleinlagerung folgt eine Beobachtungsphase (Planungsannahme 50 Jahre), nach deren Ende ein Gesuch um Lagerverschluss gestellt werden wird. Das Kapitel enthält eine Zusammenfassung der verschiedenen Abfalltypen und -mengen, die in Kernkraftwerken sowie in der Medizin, Industrie und Forschung anfallen, sowie eine Darstellung der Sicherheitskonzepte für die beiden Lagertypen.

In Kapitel 3 werden die Methodik und das Vorgehen bei der Planung der RD&D-Aktivitäten diskutiert sowie die verschiedenen Kategorien von Anforderungen, welche die Art und den Zeitplan des Programms bzw. der RD&D-Aktivitäten bestimmen. Die Anforderungskategorien umfassen: Gesetzliche und behördliche Vorgaben, Vorgaben der Entsorgungspflichtigen, Erwartungen der Behörden, Erwartungen der Fachwelt und Öffentlichkeit, Anforderungen aus Technik und Wissenschaft. Daraus ergibt sich der Rahmen für die im Programm zu untersuchenden Fragestellungen und für die Art und die zeitliche Abfolge der verschiedenen technischen und wissenschaftlichen Arbeiten.

Kapitel 4 fasst die durch die Nagra identifizierten RD&D-Fragestellungen für BE/HAA aus dem Projekt Entsorgungsnachweis zusammen, einschliesslich der Empfehlungen der Behörden und Experten, die sich aus den vom Bund verlangten formalen Reviews des Projekts ergaben. Die übergeordneten Arbeitsgebiete für die Entwicklung des SMA-Lagers werden ebenfalls identifiziert. Ferner wird der Entwicklungsstand der verschiedenen Technologien, die für die Lagerrealisierung erforderlich sind, im Kontext des weltweiten Fortschritts in der Entwicklung verschiedener Technologiebereiche diskutiert.

In Kapitel 5 werden die strategischen Anforderungen für die Realisierung der beiden Lagertypen erarbeitet. Die Festlegung der zu entsorgenden Abfälle, deren Eigenschaften, die gesetzlichen und behördlichen Vorgaben sowie die technisch-wissenschaftlichen Anforderungen für die Entsorgung setzen die Rahmenbedingungen sowohl für den zeitlichen Ablauf der Lagerrealisierung als auch für die Lagerkonzepte, die für eine sichere Entsorgung der Abfälle erforderlich sind. Bei den Lagerkonzepten ist vorgesehen, dass die Langzeitsicherheit durch gestaffelte passive Sicherheitsbarrieren gewährleistet wird, wobei die geologischen und technischen Barrieren ausgewogene Beiträge leisten sollen. Die Lagerkonzepte umfassen die folgenden Elemente: i) das Hauptlager, in dem die Abfälle eingelagert werden und das innerhalb einer angemessenen Zeit nach der Einlagerung verfüllt und versiegelt wird; ii) das Testlager, in dem standortspezifische Daten für die relevanten Eigenschaften des Wirtgesteins zwecks Bestätigung der Sicherheit und technischen Machbarkeit erhoben werden; iii) das Pilotlager, in dem das Verhalten der Abfälle, der Verfüllmaterialien und des Wirtgesteins bis zum Ende der Beobachtungsphase mit dem Ziel überwacht werden, Daten für die Bestätigung der Sicherheit im Hinblick auf den Lagerverschluss zu sammeln. Wirtgesteine mit günstigen Eigenschaften sind innerhalb von geologisch-tektonisch stabilen Grossräumen auszuwählen, um einen angemessenen Beitrag der geologischen Barriere zu den Sicherheitsfunktionen zu gewährleisten.

Das Sachplanverfahren wird danach im Hinblick auf die Anforderungen an das RD&D-Programm der Nagra für alle Etappen der Standortwahl bis zum Rahmenbewilligungsgesuch erläutert. Für Etappe 1 (Auswahl von geologischen Standortgebieten) werden die Schritte zusammengefasst, welche zum Vorschlag der Nagra von sechs geologischen Standortgebieten für das SMA-Lager (Südranden, Zürcher Weinland, Nördlich Lägeren, Bözberg, Jura-Südfuss, Wellenberg) und drei geologischen Standortgebieten für das HAA-Lager (Zürcher Weinland, Nördlich Lägeren, Bözberg) geführt haben. In Etappe 2 sind mindestens zwei Standorte je für das SMA- und das HAA-Lager auszuwählen und in Etappe 3 erfolgt die Standortwahl für das SMA- und HAA-Lager, für welche je ein Rahmenbewilligungsgesuch auszuarbeiten ist. Der bestehende Detaillierungsgrad der Anforderungen aus dem Sachplan, kombiniert mit den Resultaten des früheren Arbeitsprogramms, ergibt eine recht klare Definition der RD&D-Aktivitäten und der erwarteten Hauptberichte für die verschiedenen Etappen auf dem Weg zum Rahmenbewilligungsgesuch.

Für die nachfolgenden Schritte der Lagerrealisierung, d.h. Bau und Betrieb eines Felslabors am ausgewählten Standort, Bau und Betrieb des Lagers bis zum Verschluss, wird die Art der durchzuführenden Arbeiten definiert. Dies erlaubt es, für jede Etappe den erforderlichen Reifegrad von wissenschaftlichen und technischen Erkenntnissen so festzulegen, dass die RD&D-Untersuchungen zeitgerecht geplant und die Ressourcen wirksam eingesetzt werden können.

Kapitel 6 vermittelt eine Übersicht der in den nächsten 5 bis 10 Jahren, d.h. innerhalb der Zeitspanne bis zum Rahmenbewilligungsgesuch, durchzuführenden Arbeiten, einschliesslich der Zielsetzungen, Rollen und Schwerpunkte der verschiedenen Arbeitsbereiche. Diese Arbeiten umfassen:

- Geologische Untersuchungen (Erfüllung der Anforderungen an die Eigenschaften und an die Geometrie der Wirtgesteine und Rahmengesteine sowie an die geologische Langzeit-entwicklung; Daten für sicherheitsrelevante Schlüsselparameter)
- Sicherheitsanalyse (Erfüllung der Anforderungen an die Betriebssicherheit und Langzeit-sicherheit)
- Radioaktive Abfälle und Materialien (Erfüllung der Anforderungen an die Abfälle)
- Technische Lagerkonzepte, einschliesslich Konzepte für die Rückholung der Abfälle und für die Beobachtungsphase. Dies umfasst auch die Konzepte für die technischen Barrieren und für deren Verhalten (Erfüllung der Anforderungen an die Lagerauslegung).

Résumé

La Nagra a pour mission de planifier en Suisse des dépôts géologiques sûrs permettant de stocker tous les types de déchets radioactifs produits sur le territoire national. Deux types de dépôts sont prévus, l'un pour les déchets de faible et de moyenne activité (DFMA) et l'autre pour les éléments combustibles usés, les déchets de haute activité vitrifiés et les déchets de moyenne activité à vie longue (AC/DHA/DMAL). Du fait que le processus qui conduira à la réalisation des dépôts se déroulera par étapes sur plusieurs dizaines d'années, il est nécessaire de disposer d'un plan de recherche-développement-démonstration («plan RD&D») global permettant de planifier les travaux scientifiques et techniques. Le plan a pour fonction principale d'établir – sur la base des différentes prescriptions, contraintes et hypothèses de conception – les objectifs, l'envergure, la nature et le calendrier des futures activités de RD&D.

Le chapitre 1 présente the objectifs généraux du rapport et un bref rappel historique. En 2006, une décision du gouvernement fédéral a établi que la Nagra, avec son projet *Entsorgungsnachweis* («démonstration de la faisabilité du stockage»), avait démontré que l'évacuation en Suisse des AC/DHA/DMAL était techniquement réalisable. Sur la base d'études antérieures et d'expertises des autorités de sûreté, le Conseil fédéral avait déjà reconnu la faisabilité globale d'une évacuation sûre des DFMA. A la suite de la décision concernant l'étude de faisabilité *Entsorgungsnachweis*, le gouvernement fédéral a approuvé en avril 2008 le plan sectoriel «Dépôts en couches géologiques profondes», qui définit la procédure de sélection des sites d'implantation. La «conception générale» du plan sectoriel décrit les objectifs concrets visés par la Confédération, ainsi que les modalités selon lesquelles on sélectionnera les sites d'implantation appropriés pour les DFMA et les AC/DHA/DMAL, qui feront ultérieurement l'objet d'une demande d'autorisation générale. La planification globale présentée ici est basée sur les propositions effectuées par la Nagra dans le cadre de l'étape 1 du plan sectoriel, qui doit aboutir à la sélection de domaines d'implantation géologiques appropriés.

Le chapitre 2 présente les conditions globales de planification pour la réalisation des dépôts pour DFMA et AC/DHA/DMAL, en particulier le cadre temporel envisagé, les types et quantités de déchets ainsi que la stratégie adoptée pour garantir la sûreté des dépôts. Le calendrier prévisionnel prend en compte la procédure du plan sectoriel, la demande d'autorisation générale, la construction et l'exploitation des laboratoires de recherche souterrains sur les sites d'implantation, la demande d'autorisation de construire suivie de la construction des dépôts et enfin la demande d'autorisation d'exploiter les installations. Selon les prévisions actuelles, le dépôt des DFMA pourrait être en activité à partir d'environ 2035, celui des AC/DHA/DMAL aux alentours de 2050. La période d'emmagasinage des déchets sera suivie d'une phase d'observation (dont la durée a été fixée à 50 ans pour les besoins de la planification), à la fin de laquelle on soumettra une demande d'autorisation de fermeture. Ce chapitre comprend en outre un aperçu des différents types et quantités de déchets produits par les centrales nucléaires, ainsi que par la médecine, l'industrie et la recherche. Il décrit enfin les concepts de sûreté pour les deux types de dépôts.

Le chapitre 3 est consacré à la méthodologie et à la procédure utilisées pour planifier les activités de RD&D. Il présente les différents types de prescriptions et de contraintes qui gouvernent la nature et la répartition dans le temps du programme et des activités de RD&D: le cadre légal, réglementaire et politique, les exigences émanant des producteurs de déchets, les recommandations effectuées par les autorités, les attentes de la société et enfin les contraintes techniques et liées à la sûreté. Ce cadre prescriptif détermine les questions à traiter dans le programme de RD&D, de même que la nature et le calendrier des diverses activités scientifiques et techniques.

Le chapitre 4 présente brièvement les questions à clarifier pour les AC/DHA/DMAL, identifiées par la Nagra dans le cadre du projet *Entsorgungsnachweis,* ainsi que les recommandations effectuées par les autorités lors de l'examen officiel exigé par le gouvernement fédéral. Les activités de RD&D nécessaires pour la planification d'un dépôt pour DFMA sont également énumérées. Pour chacune des technologies intervenant dans la réalisation des dépôts, le stade de développement est évoqué dans le contexte de l'avancement technologique du domaine correspondant au niveau international.

Le chapitre 5 décrit le cadre stratégique qui prévaut lors de la conception des deux types de dépôts. Le calendrier de réalisation, de même que les concepts de dépôts nécessaires à un stockage sûr des déchets, sont conditionnés par la définition des types de déchets, leurs caractéristiques et le cadre légal et réglementaire en matière d'évacuation. La sûreté à long terme des dépôts doit être garantie par une succession de barrières de sûreté passives, dont l'efficacité est également partagée entre les barrières ouvragées et la géologie environnante. Les concepts de dépôts en couches géologiques profondes prévoient: i) un dépôt principal dont les galeries seront comblées et scellées lorsque les déchets auront été emmagasinés, ii) des zones expérimentales, où l'on recueillera les données nécessaires sur les caractéristiques de la roche d'accueil, afin de confirmer la sûreté à long terme du dépôt et la faisabilité technique, iii) un dépôt pilote où le comportement des déchets, du matériau de comblement et de la roche d'accueil feront l'objet d'une surveillance jusqu'à la fin de la phase d'observation et où l'on compilera les données permettant de confirmer la sûreté du dépôt en vue de sa fermeture. Les roches d'accueil présentant des caractéristiques favorables doivent être sélectionnées au sein de domaines géotectoniques stables et suffisamment étendus, de façon à ce que les barrières géologiques contribuent de manière efficace à la sûreté du dépôt.

La procédure de plan sectoriel est ensuite détaillée afin de montrer ses implications pour le programme de RD&D de la Nagra à chacune des étapes de la sélection des sites d'implantation et lors de la demande d'autorisation générale. Pour l'étape 1, qui correspond à la sélection de domaines géologiques appropriés, on décrit la démarche qui a abouti à la proposition des six domaines d'implantation géologiques pour le dépôt de DFMA («Schaffhouse-Sud», «Weinland zurichois», «Nord des Lägeren», «Bözberg», «Pied sud du Jura» et «Wellenberg») et les trois domaines d'implantation géologiques pour le dépôt de AC/DHA/DMAL («Weinland zurichois», «Nord des Lägeren», «Bözberg»). L'étape 2 doit aboutir à la sélection d'au moins deux sites d'implantation pour les dépôts de DFMA et AC/DHA/DMAL. Elle sera suivie de l'étape 3, où un site sera sélectionné pour chacun des dépôts en vue de la demande d'autorisation générale. Les exigences précises formulées dans le plan sectoriel, alliées aux résultats obtenus lors des programmes de recherche antérieurs, ont permis de définir avec une assez grande précision les activités de RD&D et les principaux rapports nécessaires à chacune des étapes précédant la demande d'autorisation générale.

Pour les étapes ultérieures – à savoir la construction et l'exploitation du laboratoire souterrain sur les sites s'implantation choisis, la construction des dépôts, leur exploitation et enfin leur fermeture –, les travaux à effectuer sont décrits dans leurs grandes lignes. Ceci permet de spécifier le niveau de maturité scientifique et technique requis à chaque étape, pour une répartition appropriée des études de RD&D dans le temps et une gestion efficace des ressources.

Le chapitre 6 fournit un aperçu des travaux de RD&D à effectuer dans les prochains 5 à 10 ans, c'est-à-dire avant la demande d'autorisation générale, et indique les objectifs à atteindre, l'état actuel des connaissances et les thèmes de recherche principaux pour chacun des domaines, à savoir:

- les campagnes de reconnaissance géologiques (en conformité avec les prescriptions relatives d'une part aux caractéristiques et à la géométrie des roches d'accueil et des formations encaissantes et d'autre part à l'évolution géologique à long terme; compilation de données sur les principaux paramètres déterminants pour la sûreté du dépôt)

- l'analyse de sûreté (en conformité avec les prescriptions concernant la sûreté en phase d'exploitation et la sûreté à long terme)
- les déchets et matières radioactives (en conformité avec les prescriptions relatives aux déchets)
- les concepts relatifs à l'architecture des dépôts, y compris les concepts pour la récupération des déchets et la surveillance des dépôts, de même que la conception du système de barrières ouvragées et de leur performance (en conformité avec les prescriptions relatives à la conception des dépôts).

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1 Introduction

1.1 Background to and scope and objectives of the report

Nagra's mission and strategy

Nagra's mission is to develop safe geological repositories in Switzerland for all radioactive wastes arising in Switzerland. In so doing, Nagra must develop the plans for repository implementation and the scientific and technical basis for evaluating their safety and must also assess the overall costs. The planning strategy involves developing proposals for siting two types of repositories, one for spent fuel (SF), high-level waste (HLW) and long-lived intermediate-level waste (ILW), referred to hereafter as the HLW repository and one for low- and intermediate-level waste (the L/ILW repository), and to prepare corresponding general licence applications according to the timetable foreseen. After the general licences have been granted, underground exploration will take place, including the implementation of site-specific Underground Research Laboratories (URLs) that will eventually lead to nuclear construction and later to operation licences. The two types of repositories may be at separate sites or co-located at the same site (a "combined" repository).

After about 30 years of work by Nagra of developing the scientific basis for safe repositories[1], the Federal Government accepted in June 2006 that Nagra had successfully shown through "Project Entsorgungsnachweis" (Nagra 2002a, b and c) that disposal of HLW in Switzerland is technically feasible; the demonstration of technical feasibility of disposal of L/ILW by Nagra had already been accepted by the Federal Government in 1988. Thus, the phase of siting the repositories can now be started. In April of 2008, the Federal Government approved the details of the Sectoral Plan for Geological Repositories (*Sachplan geologische Tiefenlager*) (FOE 2008). The Sectoral Plan defines the process for selection of sites for repositories for geological disposal of radioactive wastes for which general licence applications will be prepared, the next major milestone in the RD&D plan. This process should occur in a clear and transparent way. It clearly defines the roles of the different stakeholders based on the Nuclear Energy Act (KEG 2003) as well as the decision-making process and the input needed for the decision-making. The establishment of this process and the way in which responsibilities are defined have important implications for Nagra's future studies and the timing of various activities over the next ~10 years which are elaborated here.

The basic elements of waste management in Switzerland are schematically illustrated in Figure 1-1.

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[1] This includes the development of repository concepts and the underlying safety concepts, the development of the corresponding syntheses and documentation (safety cases, geological syntheses, description of design concepts), an evaluation of possible host rocks and their occurrence, the implementation of an experienced team and the necessary infrastructure (including URLs).

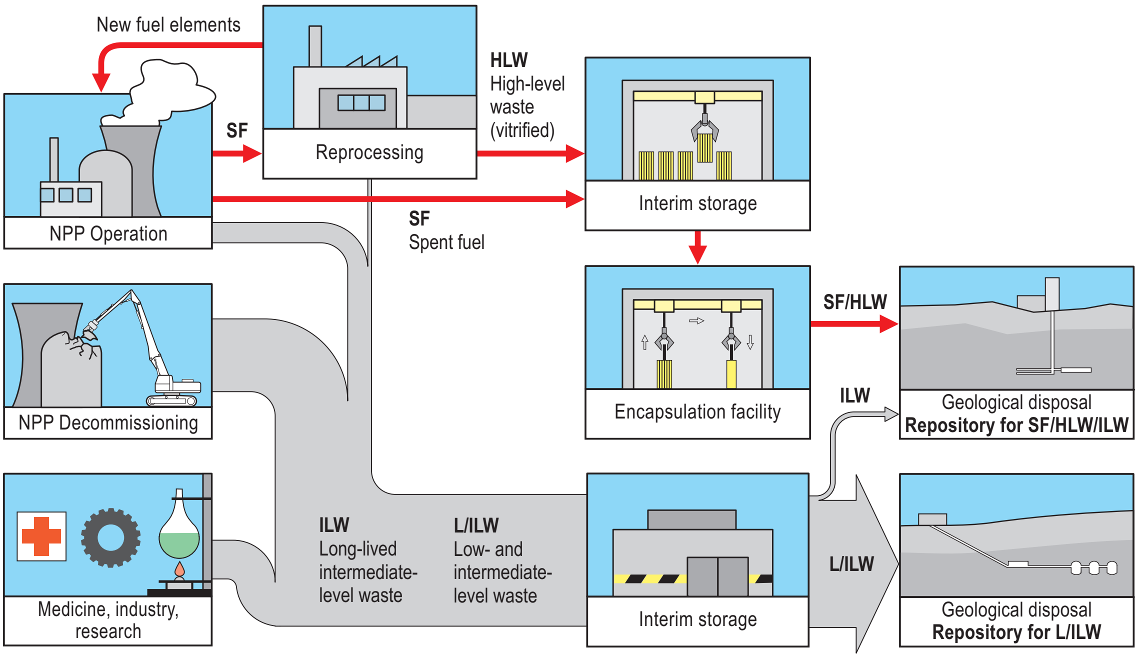

Fig. 1-1: Schematic illustration of the basic elements of radioactive waste management in Switzerland.

The present report presents both a strategic plan for Nagra's RD&D for implementation of HLW and L/ILW repositories and a programme of technical work consistent with the strategic objectives.

Scope and objectives of the report

The overall objectives and scope of this report include:

- Discussion of the RD&D-requirements related to stepwise implementation of the HLW and L/ILW repositories and the planning assumptions consistent with these requirements, including the overall long-term (~ 20 to 40 years) plan for repository implementation, with emphasis on defining the factors that dictate the developments needed at each stage of repository development
- An overview of the steps and requirements of the Sectoral Plan and the subsequent general licence applications, the key reports and deliverables required and the associated RD&D – the Sectoral Plan and the general licence applications define the work over the next ~10 years.
- A summary of the key issues raised by the various formal reviews of Project Entsorgungsnachweis (demonstration of disposal feasibility)
- A summary of Nagra proposals of siting regions for repositories for HLW and L/ILW (i.e. Nagra's formal proposals for Stage 1 of the Sectoral Plan process, see Chapter 5 and Nagra 2008c)
- A discussion of the technical programme of work for the next ~ 10 years, based on the points above and Nagra's recommended siting regions as input to Stage 1 of the Sectoral Plan

The main objective of the RD&D Plan is thus to establish the purpose, scope, nature and timing of various future RD&D activities, starting from the broad planning assumptions presented in the following sections and drawing on various syntheses of earlier and ongoing technical work.

The target audience of this report is mainly the international waste management community, Nagra's partner organisations, the interested public and the Swiss authorities[2].

The RD&D Plan focuses on assessing and outlining the work required to further develop Nagra's science and engineering base and to ensure that the technology, data and expertise necessary to achieve future milestones in repository planning and development, including eventual implementation, are acquired in a timely and cost-effective manner. The assumptions underlying the RD&D Plan are derived from a strategic planning document referred to as the "Entsorgungsprogramm" (Waste Management Programme; Nagra 2008a), which fulfils a formal requirement defined in the Nuclear Energy Act (KEG 2003) to propose to the federal government a programme and financing plan for repository implementation. Of particular relevance to the RD&D Plan and Programme is the Nagra strategy underlying the response to the issues quoted in Box 1-1.

Box 1-1: Key issues in federal law regarding the Waste Management Programme.

The waste producers must make proposals in the Waste Management Programme regarding (KEV 2004):

(a) the origin, type and quantities of radioactive waste

(b) the required geological repositories including the layout concepts

(c) the allocation of the wastes to the repositories

(d) the plan for realisation of the geological repositories

(e) the duration and required capacity of facilities for the centralised and decentralised interim storage

(f) the finance plan for work related to disposal up to the time of end of operation, with proposals for:

1. the necessary work
2. the costs
3. the nature of the financing

(g) the information concept

The report is organised in the following way:

- Chapter 1 presents the overall objectives of the report and a brief history of the steps leading to the present situation.
- Chapter 2 presents the planning premises, including waste arisings, an overview of long-term repository planning, resources of the programme, and the safety strategy and the concepts for geological repositories for HLW and L/ILW in Switzerland.

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[2] For this report, however, there is no formal request, thus there will not be a formal review by the Swiss authorities.

- Chapter 3 discusses the RD&D planning process and planning methodology and the various categories of requirements that dictate the nature and timing of the programme and the planned RD&D.
- Chapter 4 reviews the status of the HLW and L/ILW programmes, including:
  - the key technical and scientific considerations related to important decisions, including the factors related to the strong focus on Opalinus Clay relative to other host rocks for the HLW repository
  - the outcomes of the reviews of Project Entsorgungsnachweis and Project Wellenberg, in relation to the scientific and technical status of work relevant to repository implementation, including Nagra's own assessment and the reviews by the authorities; these projects and the associated reviews identified issues and gaps for future stages of development[3]
  - the proposal of the siting regions for the HLW and L/ILW repositories, details of which are discussed in Chapter 5 and in Nagra (2008c)
  - the status of worldwide disposal technology development from the perspective of the present and expected future technical maturity in areas that are relevant to Nagra's repository implementation plans
- Chapter 5 outlines the strategic requirements and assumptions associated with RD&D planning, including:
  - a summary of the Sectoral Plan process for selecting sites for geological repositories, with particular emphasis on Nagra's responsibilities within this process and the requirements on the general licence applications to be prepared for the sites selected
  - the specific requirements for the repository concepts and design
  - the specific requirements for the various repository development stages and the strategic assumptions on which the RD&D programme of work is based (Nagra 2008a), including a summary of Nagra's proposals for siting regions for Stage 1 of the Sectoral Plan (Nagra 2008c)
- Chapter 6 gives an overview of the RD&D work to be done in the next 5 to 10 years, including the objectives, status and principal focus in the following areas of work:
  - geological investigations (compliance with requirements for properties and geometry of host rocks and confining units and for long-term geological evolution; data for key safety-relevant parameters)
  - safety assessment (compliance with requirements for operational and long-term safety)
  - radioactive waste and materials (compliance with requirements for waste)
  - repository engineering concepts, including concepts for waste retrievability and monitoring. This includes also the concepts for the engineered barrier system and their performance (compliance with requirements for repository design).

It is noted that the RD&D programme of work is conditioned by the assumption that Nagra's recently submitted proposals (Nagra 2008c) regarding siting regions and associated host rocks for repositories will be confirmed in the review process for Stage 1 of the Sectoral Plan for Geological Repositories. Furthermore, Nagra recognises that the basic strategic assumptions for

[3] It is noted that a complementary document to this one focuses point-by-point on each of the recommendations made in the reviews of Project Entsorgungsnachweis for the HLW repository by the authorities (Nagra 2008b).

the RD&D programme will inevitably be revised at the end of Stage 2 when narrowing down to potential specific sites will occur, thus the RD&D plan will need to be reviewed and revised at that time.

1.2 The path to site selection – 30 years of research and geoscientific studies and legal and institutional developments

The following provides an overview of the events and decisions leading to the initiation of the Sectoral Plan for Geological Repositories, which serves to select sites for implementing the HLW and the L/ILW repositories. Scientific and technical aspects related to some of these developments are discussed in more detail in Chapter 4.

The legal basis and establishment of Nagra

The management of radioactive waste has been explicitly addressed by the Swiss Federal Government from the very beginning of Switzerland's nuclear programme. The fundamental aspects were defined in the Atomic Act (1959), and they were further elaborated in the Federal Government Ruling on the Atomic Act (1978) and the Radiation Protection Act (StSG 1992). The 1978 Ruling obliged the producers of radioactive waste to develop waste management solutions and to ensure the funding required for its implementation. Nagra, established as a Cooperative of the radioactive waste producers (the electric utilities and the Swiss Federation – represented on Nagra's Board by the Swiss Federal Department of Interior, which is responsible for waste from medical, industrial and research application), thus initiated the research and development programme in the late 70s and undertook the exploration of potential host rocks for proposing feasibility projects of geologic repositories for the long-term safe disposal of the waste.

The Government Ruling on the Atomic Act (1978) was accompanied by a very specific requirement to demonstrate that safe disposal of radioactive waste in Switzerland is feasible as a prerequisite to continue operation of the existing nuclear power plants and the construction of any new nuclear power plants. Demonstration of feasibility included the following three aspects: a) engineering feasibility, i.e., concepts that can be implemented with existing technology; b) long-term safety to humans and the environment, and c) site feasibility, i.e., that there exist formations and locations in Switzerland where a) and b) above can be fulfilled.

Project Gewähr

Nagra initiated a project with these objectives called "Project Gewähr" and in 1985 submitted the associated documentation (Nagra 1985) to the Federal Government. In order to realise this project, Nagra set up an R&D programme for the development of the basic datasets and the methodologies for the conceptual development and the performance assessment of geologic repositories – for low- and intermediate-level waste (L/ILW), long-lived intermediate-level (long-lived L/ILW) and high-level waste (HLW) – as well as to acquire the supporting fundamental geoscientific data. In 1988 the government approved Project Gewähr for the L/ILW repository and approved the engineering and long-term safety parts for the HLW repository; however, it requested that Nagra extend the considerations for the geologic host formations from the crystalline basement to sedimentary formations. Figure 1-2 shows the extent of geologic formations (for the HLW programme) and specific sites (for the LLW programme) investigated by Nagra in the period 1980 to 2002.

L/ILW disposal investigations

For the L/ILW repository Nagra performed exploratory investigations in the four sites shown in Figure 1-2 (BDG: Bois de la Glaive; OBS: Oberbauenstock; PPG: Piz Pian Grand; WLB: Wellenberg). Among those, the Wellenberg site was selected as the candidate site for the L/ILW repository, following a detailed site characterisation programme and the assessment of the long-term safety of the whole system (Nagra 1993). Nagra had also obtained a permit from the Federal Government for an exploratory underground tunnel for the investigation. In 1994, Nagra submitted a general licence application which received a positive review by the safety authorities. Due to a change in the Cantonal law, a concession for utilising the underground, a resource belonging to the Canton, was subjected to a Cantonal Referendum and also Nagra's general licence application was submitted to the population of the Canton Nidwalden for comment. The Cantonal Referendum took place in 1995 and the concession was denied, by a majority of approx. 51.5 % (although the siting community did approve it); also the general licence application was turned down.

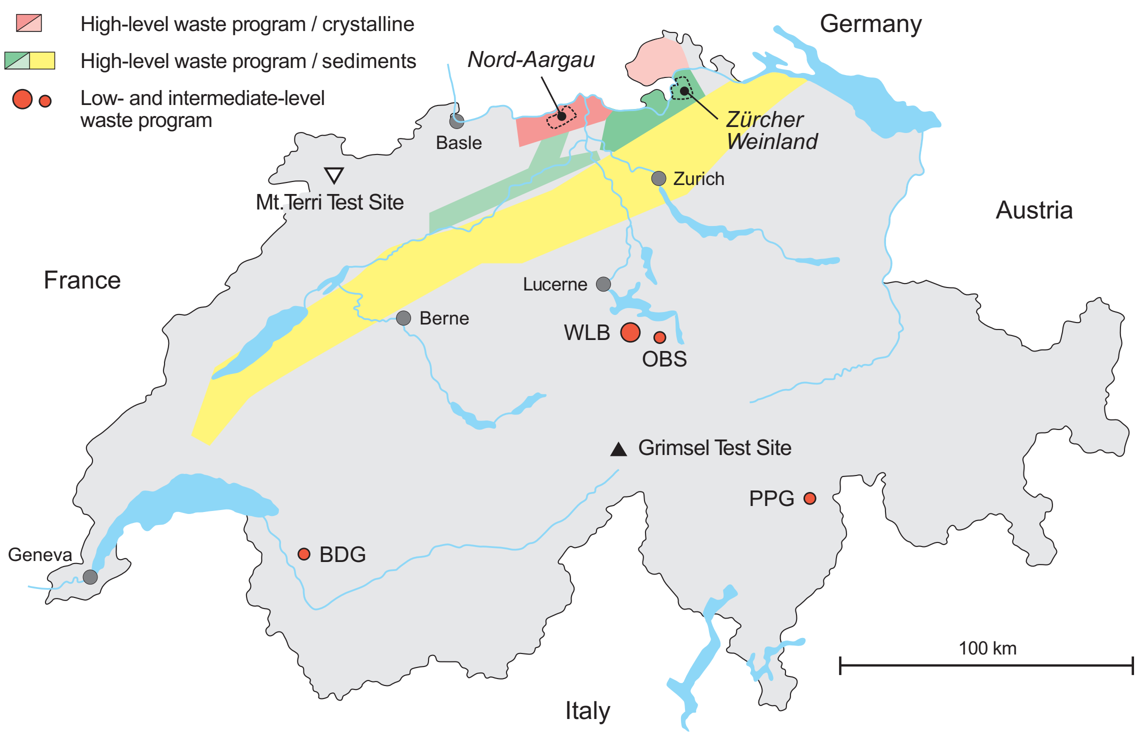

Fig. 1-2: Formations, regions and sites investigated by Nagra for the geologic disposal of radioactive waste in the period from 1980 to 2002.

Cantonal and federal reviews

The cantonal and federal governments formed different groups to analyse the results and to also find a way to proceed. Furthermore, the EKRA[4] group, established by the Federal Government, proposed adopting the concept of monitored geologic disposal (FOE 2000), as a response to

[4] EKRA (Expertengruppe Entsorgungskonzepte für radioaktive Abfälle): An expert group established by the Federal Department of the Environment, Transport, Energy and Communication (DETEC).

societal wishes concerning monitoring and retrievability. The concept proposed by EKRA foresees a stepwise implementation of the repository including the final part, namely the closure of the repository. A pilot facility should be constructed as the first part of the actual repository, with geometrical and engineering characteristics being the same as the actual repository, albeit with a shorter length of the disposal caverns, and with waste, backfilling material, emplacement cavern seals as in the actual repository. It is this pilot facility that should be monitored extensively, while the main repository is being constructed, filled and closed as planned. An extended monitoring period at the end of the emplacement of all the wastes, in addition to the several decades of monitoring the pilot facility, would provide to the generation at that time a sufficiently long record of observations to decide on the final closure. This concept of a pilot facility also became an integral aspect of the HLW repository concept and was incorporated into Project Entsorgungsnachweis (2002b and c).

The Wellenberg design was also modified to consider these changes, as shown in Figure 1-3. The new proposal was brought to a Cantonal Referendum in 2002 – requesting a permit and concession for the exploratory tunnels. Despite the favourable evaluation of the proposals and of the whole project by the Nuclear Safety Inspectorate HSK[5] (HSK 2001) and also from the cantonal technical group, the requests were denied for a second time in a cantonal referendum, leading to a deadlock for any further steps, although the siting community of Wolfenschiessen accepted the project in all of the public votes.

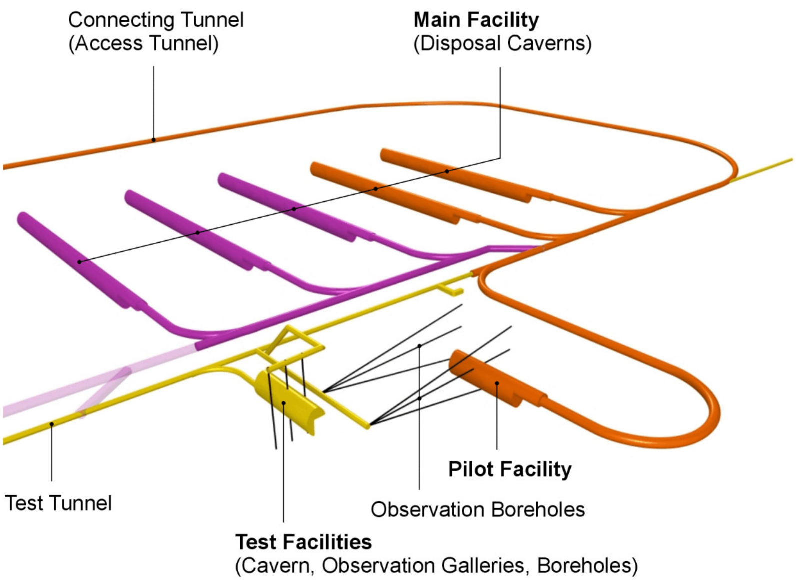

Fig. 1-3: Illustration of the monitored geologic repository concept for the L/ILW repository.

The Pilot Facility is constructed as the first part of the repository with the same type of waste and engineered barriers as the Main Facility.

HLW Investigations and Project Entsorgungsnachweis

Nagra pursued studies related to evaluating sedimentary rocks for disposal of HLW from the mid-1980s through the 1990s and submitted Project Entsorgungsnachweis to the Federal Government for review in December 2002. This project, which is based on the Opalinus Clay

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[5] Since January 1st 2009 HSK is independent of the licensing authority (Federal Office of Energy, FOE) and is now named 'Eidgenössisches Nuklearsicherheitsinspektorat ENSI'.

host rock option and on the potential siting region in the Zürcher Weinland, was an important milestone in the programme for disposal of HLW. The principal emphasis was on demonstrating that a site with suitable characteristics could be found and characterised, and that, based on its properties, safety and engineering feasibility could be demonstrated. When submitting Project Entsorgungsnachweis, due to the excellent project results, Nagra also asked the Federal Government to allow future work for implementing the HLW repository to focus on the Opalinus Clay as host rock and on the Zürcher Weinland as siting region. During the authority review, Nagra was asked to prepare a report on the different siting options for a HLW repository. Nagra submitted this report in August 2005 (Nagra 2005). In this report, the Opalinus Clay is identified as the preferred host rock for a HLW repository, whereas the crystalline basement in Northern Switzerland and the Lower Freshwater Molasse (USM) are considered as reserve options. Furthermore, the report also discusses the broad regions suited to siting the HLW repository and qualifies them in broad terms.

In August 2005, all the extensive reviews by the Nuclear Safety Inspectorate (HSK), the Commission on Nuclear Safety (KSA), the Commission on Nuclear Waste Management (KNE) and the International Review Team (IRT) of the OECD Nuclear Energy Agency on Project Entsorgungsnachweis were made available. They all came to positive conclusions and HSK recommended to the Federal Government to accept the demonstration of feasibility. However, in the reviews a large number of recommendations were made (Nagra 2008b) regarding studies that should be done in relation to future development stages (see Chapter 4). In June 2006, the Federal Government decided that Nagra had successfully shown that safe disposal of HLW in Switzerland is technically feasible. In the same decision, the Federal Council refused the recommendation to focus further investigations on the Zürcher Weinland and stated that the search for a disposal site should be continued using a sectoral planning process.

The current legal framework and the Sectoral Plan for Geologic Repositories

During 2002, two initiatives were formulated at the national level, requesting in essence either a moratorium for new nuclear power plants or the phasing out of nuclear energy in Switzerland. In response to these initiatives, the Federal Government revisited the Atomic Act and on 21 March 2003 proposed the new Nuclear Energy Act encompassing articles for nuclear energy generation as well as radioactive waste. The national referenda proposing a moratorium or the phasing out of nuclear energy were not approved by the Swiss population and the Nuclear Energy Act and the respective Nuclear Ordinance became effective in 2005.

The following three acts (and the corresponding Ordinances) define the legal framework for geological disposal of radioactive waste (including siting) in Switzerland:

- Nuclear Energy Act (KEG 2003)
- Environmental Protection Act (USG 1983)
- Spatial Planning Act (RPG 1979)

Of particular interest in relation to the disposal programme are the following provisions in the Nuclear Energy Act and resulting Ordinance:

- The concept of Monitored Geological Disposal, which combines passive safety with a period of monitoring, the possibility of retrievability without excessive effort during the emplacement and observation period until final closure of the repository, is required for all types of radioactive waste (based on the proposal by EKRA, FOE 2000)

- National responsibility: Licensing of site characterisation work, construction, operation and closing of a repository is the responsibility of the Federal Government (general licence: approved by the parliament and subject to facultative national referendum)
- Stronger commitment of the Federal Government by approving a waste management programme prepared by Nagra on behalf of the waste producers
- Disposal in principle within Switzerland; export (and import) possible for disposal only as exception under certain conditions
- Site selection to be based on a Sectoral Plan (a land use planning instrument of the spatial planning act) under the leadership of the Federal Government
- Reprocessing: a 10 year moratorium starting 1st July 2006

The legislation thus introduced the need for a Sectoral Plan for the site selection process as defined in the Spatial Planning Act; Sectoral Plans have in the past been defined for other infrastructure projects or installations of national importance, for example, transportation corridors, airports, etc. Because the definition of "land-use" for such projects has to be harmonised and included in the spatial planning at the Federal, Cantonal and Community level, the Sectoral Plan is an appropriate tool to address the site selection procedure. The leading role in this procedure is with the Federal Government and in particular with the Federal Office of Energy (FOE) – an office of the Federal Department of Environment, Transportation, Energy and Communication (DETEC).

The Sectoral Plan is divided into two parts. The first part, the Concept Part, has to be defined for the particular issue, in this case the geologic repository. This part not only includes the procedure and the roles of the various participants, but also the criteria that have to be used at the various decision points and the timing and sequence of the activities.

The first draft of the concept of the Sectoral Plan was developed by FOE during 2006 following discussions and intensive participatory workshops, the latter covering a wide spectrum of stakeholders. The draft was circulated for comment to the other Federal and Cantonal Departments, authorities and their advisory committees, as well as to the waste producers, Nagra and various interest groups and the general public. In January of 2007, a revised version was produced and circulated again for comment. In the beginning of 2008 the final version was prepared and circulated in the Federal Departments for any final comments. On 2nd April 2008 the Federal Government approved the Concept Part of the Sectoral Plan, which allowed the initiation of the second part, the implementation, which will lead to the general licence applications for one geologic repository for HLW and one for L/ILW. In mid-October Nagra submitted a proposal with six siting regions that are to be further considered (Nagra 2008c).

Further information on the Sectoral Plan, with specific emphasis on Nagra's role in the implementation and the implications for RD&D, is presented in Chapter 5. The full document is available from FOE (FOE 2008).

2 Overview of implementation plan and underlying assumptions in relation to stepwise repository development

2.1 Implementation plan

Implementation of the repositories for radioactive wastes involves a staged process that can be described by the eight phases noted below. The italics represent the specific context for the first three steps for repositories for SF/HLW/ILW and L/ILW in Switzerland.

- Feasibility of final disposal (*Project Gewähr*)
- Siting feasibility HLW *(Project Entsorgungsnachweis)* and overview of siting options for a HLW repository*;* evaluation of sites for L/ILW and development of a project for a general licence application *(Wellenberg*)
- Evaluation of options and site selection *(Sectoral Plan for geological repositories and general licence procedure)*
- Detailed site characterisation (including underground exploration)
- Construction of facility
- Operation of facility
- Observation (monitoring) phase ('post-emplacement / pre-closure phase')
- Closure of facility

With the definition of the Sectoral Plan process for selecting sites for the HLW- and L/ILW-repositories now being complete, both the short- to medium-term (~ 10 years) and long-term planning horizons can be defined. For implementation of a repository for HLW, the steps have been defined according to the schedule illustrated in Figure 2-1 (Nagra 2008a), which is based on the assumption of a nuclear programme with only the existing nuclear power plants, all of which operate for 50 years. This is the basis for cost calculations for the utilities as it sets the fees for the waste management and decommissioning funds.

The timing of the steps for the HLW repository is largely determined by the heat output of spent fuel and high-level waste, which dictate that disposal can begin only after 2040 because of thermal constraints related to the engineered barrier system and rock. Thus, in the cost study (see Nagra 2008a), the start of repository operation is assumed to be 2050.

The overall schedule for L/ILW disposal for a nuclear programme with only the existing nuclear power plants and an assumption that they will operate for 50 years is shown in Figure 2-2. In this case there are no such thermal constraints, thus the implementation schedule is driven by the duration of the consultation and approval steps for the various stages and the time required for URL construction and operation and construction of the repository.

The current discussions to prolong the operation time of at least the younger nuclear power plants (Gösgen, Leibstadt) from 50 to 60 years and the plans for new nuclear power plants would lead to prolonged operation periods and to a later closure of the repositories, but the implementation schedule would most likely not be changed.

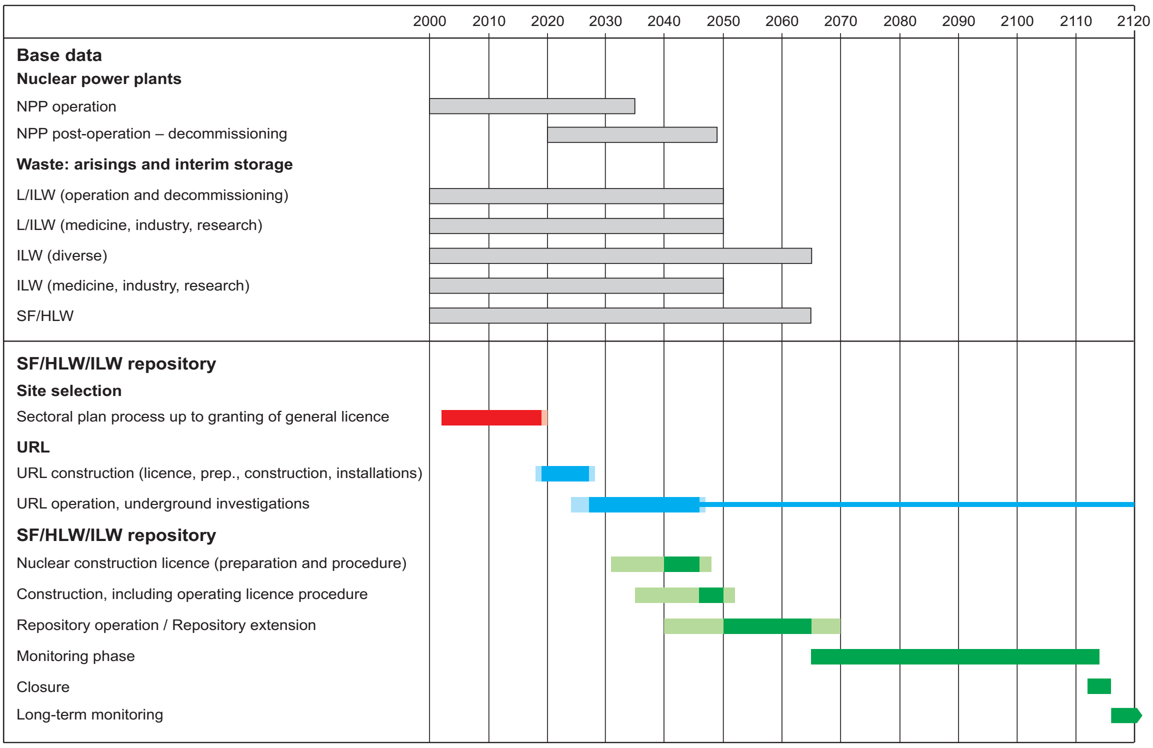


Fig. 2-1: Time plan for implementation of repository for HLW for a nuclear programme with the existing nuclear power plants and an assumption that they will operate for 50 years (Nagra 2008a).

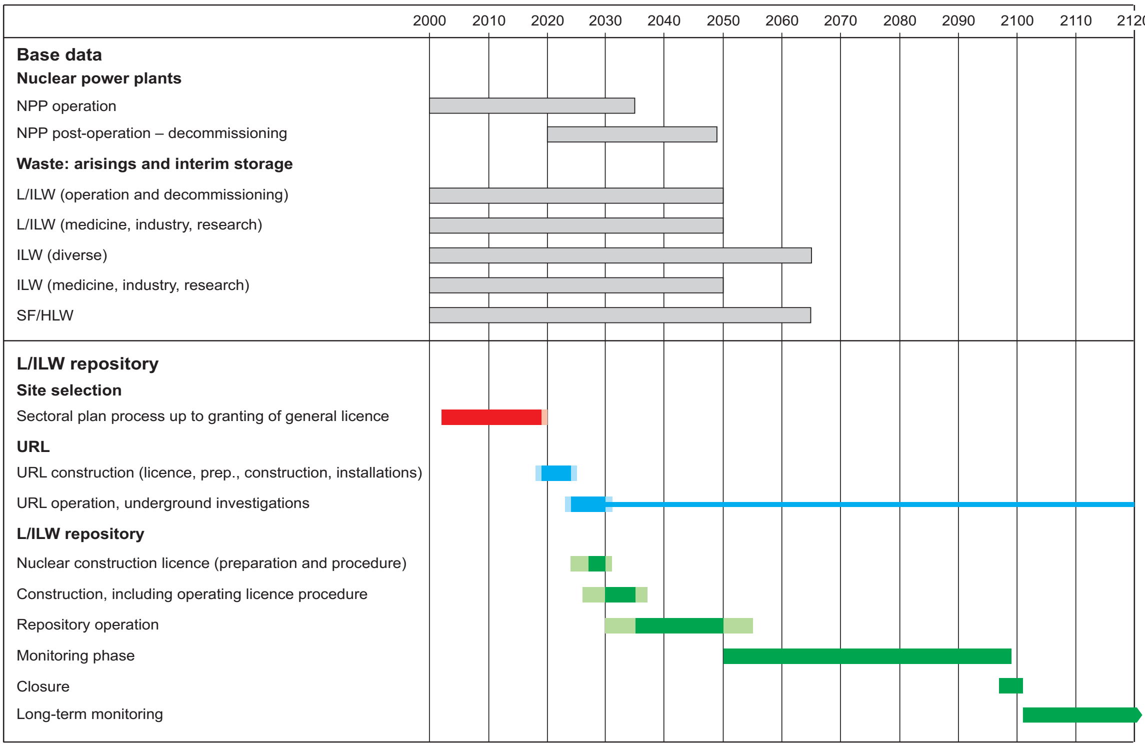


Fig. 2-2: Time plan for implementation of repository for L/ILW for a nuclear programme with only the existing nuclear power plants and an assumption that they will operate for 50 years (Nagra 2008a).

2.2 Financing of waste management

The producers of radioactive waste are obliged by law to dispose of the waste safely at their own cost. The waste management costs that arise during operation of the nuclear power plants (e.g. for reprocessing of spent fuel, investigations by Nagra, construction of interim storage facilities) are paid on an ongoing basis. The decommissioning costs and the costs of radioactive waste management arising after the nuclear power plants cease operation are secured by payments made by the owners into two independent funds, the decommissioning fund and the waste management fund.

Before the Nuclear Energy Act of 2003 came into force, the legal basis for the two funds was provided by various ordinances and regulations. On 1st February 2005, the new Nuclear Energy Act entered into force. Key provisions that were previously contained in the ordinances or regulations are now regulated at the level of federal legislation (SEFV 2007). Further details are provided in Nagra (2008a).

2.2.1 Decommissioning fund for nuclear installations

The decommissioning fund for nuclear installations was set up on 1st January 1984. The main purpose of the fund is to cover the costs of decommissioning and dismantling of disused nuclear facilities and disposing of the waste arising from these activities. The owners of the Beznau 1 and 2, Mühleberg, Gösgen and Leibstadt nuclear power plants and of the ZWILAG interim storage facility in Würenlingen are obliged to make contributions to the fund. The basis assumed for calculating the decommissioning costs and the amount of contributions to the fund is now an operating lifetime of the facilities of 50 years, except for the Mühleberg nuclear power plant where the operation licence is currently limited to 40 years. The operating period for waste management facilities will be defined in the waste management programme (see Art. 8, par. 2 and 3 of SEFV; SEFV 2007). The objective is to ensure that the presumed costs of decommissioning will be covered when the nuclear facility is taken out of operation and to distribute the contributions to the fund as evenly as possible over the time period mentioned. Decommissioning includes the dismantling of all technical installations and buildings of a nuclear power plant.

According to the most recent cost estimates, the decommissioning costs for the five nuclear power plants and for ZWILAG will amount to around 2.2 billion CHF (price basis 2006). At the end of 2007, the accumulated capital in the decommissioning fund was 1.322 billion CHF (2006: 1.324 billion CHF, 2005: 1.252 billion CHF).

2.2.2 Waste management fund for nuclear power plants

The waste management fund for nuclear power plants was set up on 1st April 2000. The purpose of the fund is to cover the costs of managing operational waste and spent fuel after the nuclear power plants have ceased operation. The owners of the Beznau 1 and 2, Mühleberg, Gösgen and Leibstadt nuclear power plants are obliged to make contributions to the fund. The first contributions to the fund were made by the power plant owners in 2001.

Waste management comprises all the activities leading up to emplacing the waste in a deep geological repository, as well as emplacement of wastes and the activities associated with a monitoring phase and closure of the repository. Costs are generated by waste treatment, reprocessing of spent fuel and interim storage and final disposal. According to the most recent cost estimates, the waste management costs will amount to around 13.4 billion CHF (price basis 2006). Part of the waste management costs arises during operation, e.g. research and preparatory work for the L/ILW and HLW repositories, reprocessing of spent fuel, construction and operation of ZWILAG, as well as waste transportation. At the end of 2005, these activities had generated costs of around 4.2 billion CHF and were met by the nuclear power plant operators on an ongoing basis. Further costs will arise up until the time when the power plants cease operation and will be met on running account. The fund will be required to accumulate around 6.3 billion CHF (due to interest rates and further payments). At the end of 2006, the accumulated capital in the waste management fund was 3.013 billion CHF (2006: 3.030 billion CHF, 2005: 2.762 billion CHF).

2.3 Types and quantities of radioactive waste

The radioactive wastes under consideration include those from operation of nuclear power plants and from medicine, industry and research. The various categories include:

1. spent fuel (SF) from the nuclear power plants when declared as waste
2. vitrified high-level waste (HLW) arising from commercial reprocessing[6] of spent fuel
3. solidified intermediate level waste (ILW), also resulting from reprocessing
4. a variety of low- and intermediate-level waste (L/ILW) from operation of nuclear power plants, future decommissioning of nuclear power plants and other nuclear facilities, hospitals, non-nuclear industries, and research

The quantities of wastes of the various categories are given in Table 2-1 for a nuclear programme with only the existing nuclear power plants and an assumption that they operate for 50 years and for a collection period for wastes from medicine, industry and research up to 2050.

Sufficient capacity for interim storage is available in the various facilities in Switzerland for all these wastes. The main centralised storage facility is ZWILAG, which has been fully operational since 2002 (see Fig. 2-3). Additional SF storage capacity exists at ZWIBEZ (the SF/HLW waste storage facility at Beznau in operation since 2007), and the wet storage facility at Gösgen (commissioned in 2008). The first storage casks of HLW arrived at ZWILAG in 2002, in addition to a number of casks of SF from the nuclear power plants. Furthermore, each of the nuclear power plants has fuel pools and interim storage for L/ILW from nuclear power plant operation. In addition, the BZL (Bundeszwischenlager) facility is operated by the Paul Scherrer Institute (PSI) for wastes from medicine, industry and research.

[6] According to the Nuclear Energy Act of 2003, there is a ten-year moratorium on exporting spent fuel for reprocessing starting 1st July 2006.

Tab. 2-1: Waste quantities in m^3 (rounded) for the case of 50 years operation of the existing nuclear power plants (NPP) and the arisings from medicine, industry and research for the period up to 2050 (Nagra 2008a).

Volumes of conditioned waste and volumes where the conditioned waste is packaged in disposal containers (numbers in brackets). The quantities are given according to origin (SF: spent fuel assemblies; HLW: vitrified high-level waste from reprocessing; RILW: intermediate-level waste from reprocessing; OW: waste from operation of NPP; DW: decommissioning waste from NPP; MIR: waste from medicine, industry and research; EF: waste from operation and decommissioning of the encapsulation facility for SF and HLW and according to the categories of the KEV, Art. 51 (HAA: hochaktive Abfälle (SF and HLW), ATA: alphatoxische Abfälle (alpha-toxic waste[7]), SMA: schwach- und mittelaktive Abfälle (low and intermediate level waste), KEV: Kernenergieverordnung (Nuclear Energy Ordinance).

		Origin							Total
		SF	HLW	RILW	OW	DW	MIR [3)]	EF	
Category according to the KEV	HAA	1'135 [1)] (6'595)	115 [2)] (730)				0.2 (2)		1'250 (7'325)
	ATA			200 [2)] (1'320)	10 (40)		325 (920)		535 (2'280)
	SMA				7'645 (26'100)	28'885 (28'920)	27'270 (32'170)	2'220 (2'220)	66'020 (89'410)
	Total	1'135 (6'595)	115 (730)	200 (1'320)	7'655 (26'140)	28'885 (28'920)	27'595 (33'090)	2'220 (2'220)	67'805 (99'015)

1 Corresponds to 2'435 tU
2 Waste resulting from reprocessing of 1'140 tU
3 This also includes the waste from decommissioning of research facilities as well as a reserve of 12'000 m^3 for L/ILW (SMA) that cannot yet be specified in detail, e.g. from CERN and PSI. It is expected that these reserves will be classified as L/ILW (SMA).

In 2008, the utilities submitted general licence applications for three nuclear power plants, two of them planned to replace the oldest Swiss facilities (Beznau 1 and 2, Mühleberg). The resulting larger waste inventory that also considers a prolonged period of collecting wastes from medicine, industry and research (MIR) is being considered for planning the repository layout and in the safety assessment studies. The detailed properties of these additional wastes are clearly not yet known in detail, thus the larger waste inventory is obtained simply by scaling the inventory of the existing nuclear power plants (assuming 60 years of operation of both the existing and the new nuclear power plants) to give a bounding inventory, with an overall waste volume of 20'000 m^3 of HLW (packaged spent fuel and vitrified HLW), 7'500 m^3 of long-lived ILW and 200'000 m^3 of L/ILW (see Nagra 2008c, e for details).

7 Alpha-toxic waste is defined as (conditioned) waste with an alpha-emitter content of > 20'000 Bq/g.

Fig. 2-3: The interim storage facility (ZWILAG) near Würenlingen (top) and a view of storage canisters containing SF and HLW (bottom).

2.4 The safety strategy and repository concepts

Radioactive waste can be stored safely in interim storage facilities. The operation of interim storage facilities, however, requires continuous monitoring and maintenance activities. Effective monitoring and maintenance presume the continued economic and political stability of our society, as well as the availability of the necessary technical know-how; however, these cannot be indefinitely guaranteed. For these reasons, very long-term (e.g. over centuries) storage in such facilities cannot be considered as a substitute for the disposal of waste in deep geological repositories.

The present safety strategy and disposal concepts for HLW and L/ILW in Switzerland are the result of many years of safety and design studies performed by Nagra (e.g. Nagra 1985, 1994a, 1994b, 2002c) and their reviews by the authorities (HSK 1986, HSK 1996, HSK 2004, HSK 2005), taking into account the relevant national legal and regulatory guidance (e.g. KEG 2003, KEV 2004, ENSI 2009[8]) as well as input from international developments.

Disposal systems must be designed and sited so that the high-level principles related to long-term safety and security (Nagra 2002a, b, c) and, more specifically, the safety functions provided by the elements of the barrier system are met (Nagra 2002a, b, c, Nagra 2008e). Furthermore, specific objectives are defined to ensure reliable implementation (Nagra 2002c). These principles, safety functions and implementation objectives are summarised below.

Principles related to siting and design

The principles related to siting and design of repositories that ensure the safety of the repositories and their reliable implementation are summarised in Table 2-2; these were outlined in Nagra (2002c) and further elaborated in Nagra (2008e).

[8] The guideline G03 (ENSI 2009) replaces the former guideline HSK-R-21 (HSK & KSA 1993).

Tab. 2-2: Principles related to siting and design.
Translated from Tab. 2.3-2 (Nagra 2008e).

Objectives	**Overall disposal principles**	
Objectives of geological disposal	Passive safety and security through deep geological disposal	
Objectives related to system	**Principles related to site**	**Principles related to design**
Safety and robustness	Multiple passive barriers to provide for safety	Multiple passive barriers to provide for safety
	Multiple safety functions provided by barrier system	Multiple safety functions provided by barrier system
	Stability and longevity of barrier system	Stability and longevity of barrier system
	Avoidance of and insensitivity to detrimental phenomena	Avoidance of and insensitivity to detrimental phenomena
	Predictability of long-term changes	Predictability of long-term changes
	Stability	Confinement and attenuation
	Favourable host rock properties	Initial complete containment
	Explorability	Redundancy
	Ability to characterise host rock properties	Reliability of implementation
		Operational safety
		Reliability of closure
Reduced likelihood and consequences of human intrusion	Preservation of repository information	Preservation of repository information
	Avoidance of resource conflicts	Compartmentalisation and waste solidification

Safety Functions

Adequate safety functions – which are provided by the elements of the barrier system of the repository – are one of the key principles ensuring long-term safety. Because of their importance, the safety functions are briefly discussed.

- **Isolation of wastes from the human environment and long-term stability** – The safety and security of the waste, including fissile material, is ensured by placing it deep underground, with all access routes backfilled and sealed, thus isolating it from the human environment and reducing the likelihood of any undesirable intrusion and misapplication of the materials. This also protects the repository from processes and events taking place at the earth's surface that could jeopardise the safety of a near-surface repository (e.g. war, civil unrest, future glaciations, erosion, …). Furthermore, by avoiding foreseeable resource conflicts, the likelihood of inadvertent human intrusion into the repository (e.g. during exploration and exploitation of natural resources) is greatly reduced.

- **Confinement of radionuclides** – Much of the activity initially present decays while the wastes are totally contained within the primary waste containers, particularly in the case of SF and HLW, for which the high integrity canisters are expected to remain unbreached for several thousand years due to the favourable geochemical and geomechanical conditions.

Even after the canisters are breached they still provide a barrier for radionuclide transport because they limit water access to the SF and HLW and because of the favourable radionuclide retention properties of canister corrosion products for many radionuclides.

- **Delayed release of radionuclides** – After canister breaching the rate at which radionuclides are released from the waste matrix is low, due to favourable geochemical conditions (specifically due to the prevailing reducing conditions). This applies specifically to SF (stable UO_2 matrix) and to HLW (stable glass matrix), but also for those long-lived ILW and L/ILW where a large fraction of radionuclides are incorporated in slowly corroding steel.
- **Radionuclide retention in the near-field and in the geosphere** – After release from the waste matrix, radionuclides are transported only very slowly through the further near-field barriers (backfill / seals) and through the host rock and the confining units due to a number of favourable properties of the technical and geological barriers (e.g. favourable geochemical conditions in the near-field and in the geosphere, low water flow in the host rock and in the confining units). During transport, further radioactive decay takes place, further reducing radionuclide release from the repository to the human environment.
- **Small release rates** – A number of additional processes attenuate releases during transport towards the human environment and limit the concentrations of radionuclides in that environment. These include radioactive decay during transport and the spreading of released radionuclides in time and space by diffusion, hydrodynamic dispersion and dilution.

The layout concept for a repository for SF, HLW and long-lived ILW that provides these safety functions is shown in Figure 2-4. For L/ILW, the repository concept is illustrated in Figure 2-5.

The way in which the engineered and natural barriers support the safety functions is illustrated in Figures 2-6, 2-7 and 2-8 for SF, HLW and L/ILW, respectively. Note that the system of barriers for disposal of long-lived ILW (see Figure 4.3-6 in Nagra 2008e) is very similar to the system of barriers for L/ILW shown in Figure 2-8.

Objectives related to stepwise implementation

Key objectives in stepwise implementation are described in Nagra (2002c). The issues of most relevance to RD&D planning are discussed below:

- **Commitment to systematic learning** – During the sequential steps, there is an increase in the body of available information, including scientific, technical, societal, institutional, and operational knowledge. Needs and questions to be addressed are made explicit at the outset. Information gained will be accepted and incorporated into the available knowledge base. One needs enough information to proceed with confidence to the next step, even if the ultimate goal is some way off. This commitment to systematic learning includes a QA system that ensures that the relevant information is made available to, and used in, future steps.
- **Involvement of stakeholders** – The stepwise approach requires the development of a safety report at each milestone. Such a safety report and other related documents (e.g. reviews) provide an excellent platform for interaction with all stakeholders, notably the regulator and policy makers, but also the scientific community and the public; and they provide an opportunity for feedback.
- **Possibilities for modification** – The approach has to provide flexibility with respect to new findings in the process of implementation. A site with spatial reserves that allows for optimal allocation of the emplacement rooms and the availability of several design options

provide flexibility. The design of the repository, conforming to the concept of monitored long-term geological disposal as proposed by EKRA, also allows the reversal of decisions in the course of the implementation process, including the retrieval of emplaced wastes.

- **Possibilities for monitoring** – The design of the repository according to the concept of monitored long-term geological disposal, as proposed by EKRA, provides opportunities for monitoring and review and possible reversal of decisions in the course of the implementation process.
- **Implementation of specific measures to ensure security during the different phases of a repository** – Specific security and safeguards measures will be implemented to ensure security in the operational phase, during the observation phase and also in the post-closure phase. Such measures are currently being discussed in international fora and are under development by international organisations.
- **Reliance on simple, well-understood and reliably characterised components** – Sites and engineered barrier systems are preferred that are simple and that can be characterised reliably to the extent required for a robust safety assessment even at an early stage of the repository. Site characterisation should preferably be possible by surface-based techniques (good explorability) and the system of engineered barriers should rely on well understood materials. This should ensure adequate predictability of the overall system. Construction of the repository and the emplacement of the engineered barrier system (EBS) must be feasible with proven technology. For development of the repository adequate quality assurance measures should be used to ensure reliable implementation.

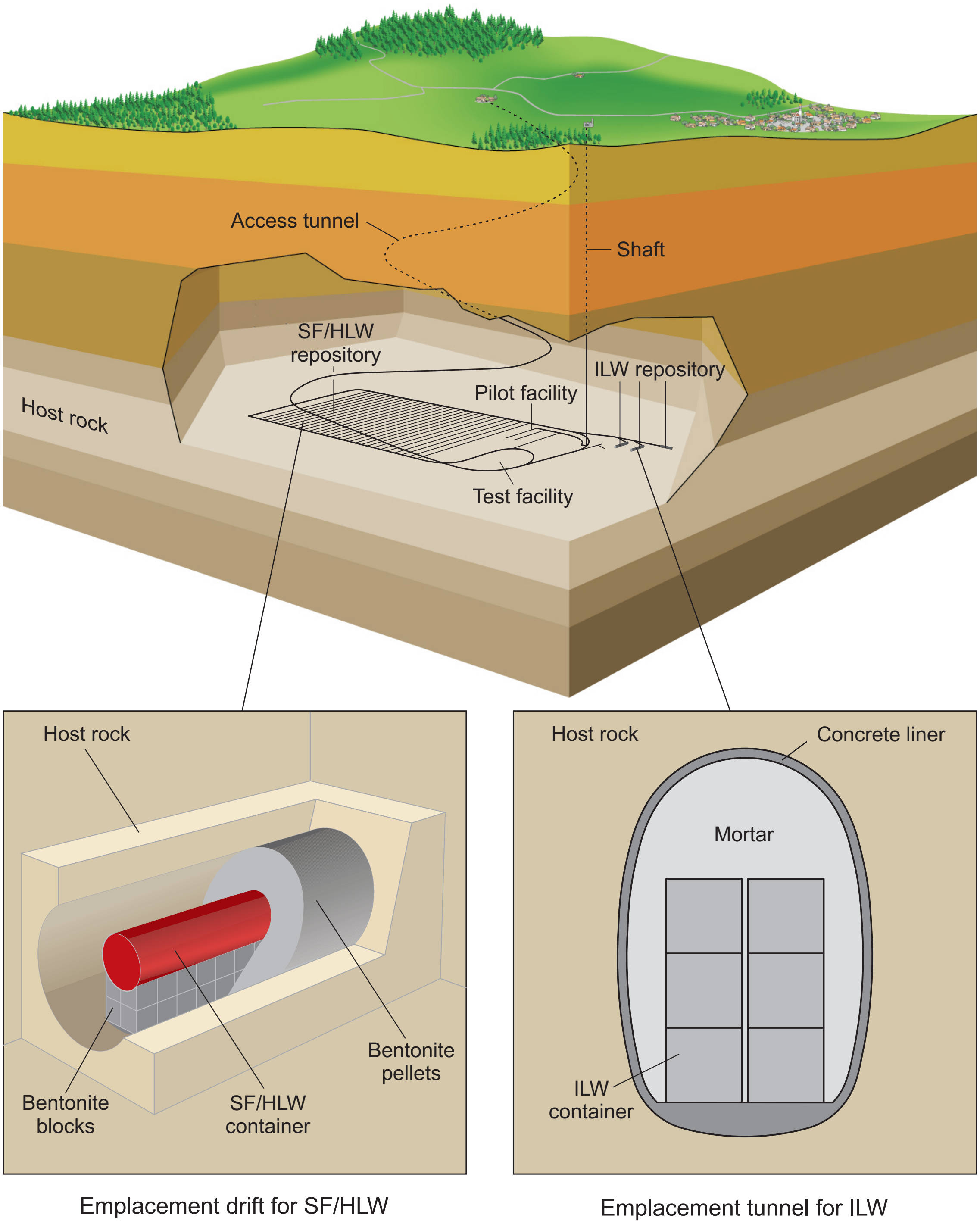


Fig. 2-4: Possible layout for a deep geological repository for SF / HLW / ILW in Opalinus Clay.

This figure corresponds to Figure 3-2 in Nagra (2008a).

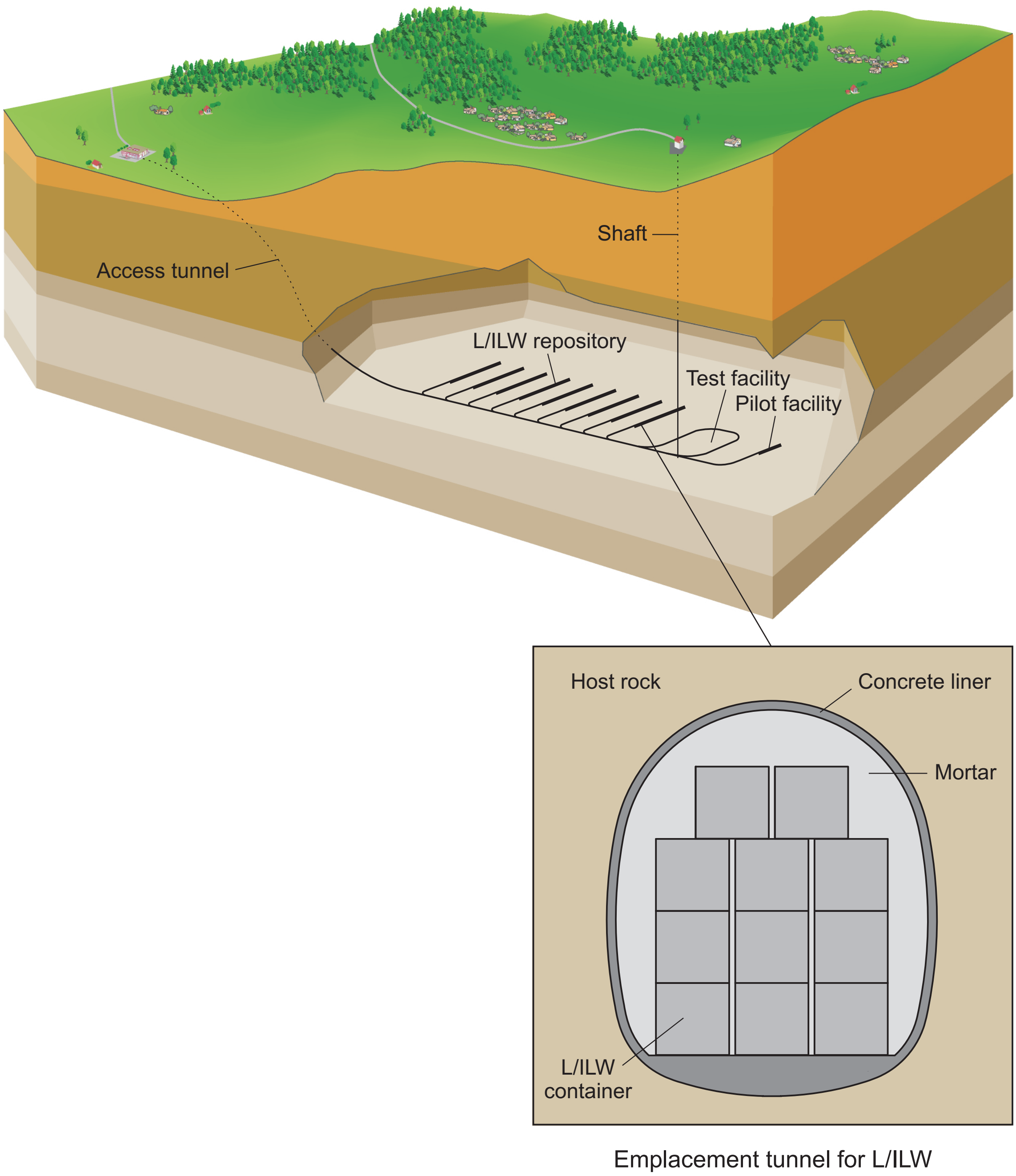


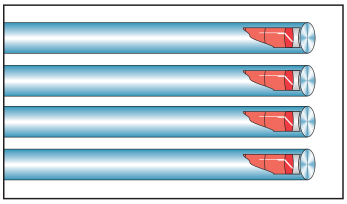
Fig. 2-5: Possible layout for a deep geological repository for L/ILW.

This figure corresponds to Figure 3-8 in Nagra (2008a).

Safety barrier system for SF

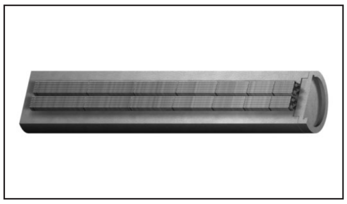
Waste matrix (UO_2/MOX)

- Fixation of radionuclides in the fuel matrix
- Low corrosion rate of the fuel matrix



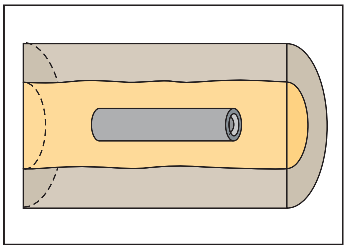
Disposal container

- Containment of the waste for several thousand years
- Thereafter: Restricted water inflow and retention of radionuclides (sorption on corrosion products)



Backfill (bentonite)

- Suitable interface between disposal containers and the host rock
- Favourable radionuclide retention properties
- Favourable conditions for long-term stability of the disposal containers



Host rock

- Low groundwater flux
- Favourable structure of the pore space
- Favourable geochemical conditions for radionuclide retention
- Favourable conditions for long-term stability of the engineered barriers

Geological situation

- Favourable host rock configuration for arrangement of the disposal tunnels
- Favourable conditions for long-term stability of the barrier system
- Absence of raw materials deposits that would be workable in the foreseeable future

Placement of disposal tunnels deep underground

- Isolation of the waste
- Prevention of unwanted access
- Protection from unintentional intrusion
- Protection from erosion

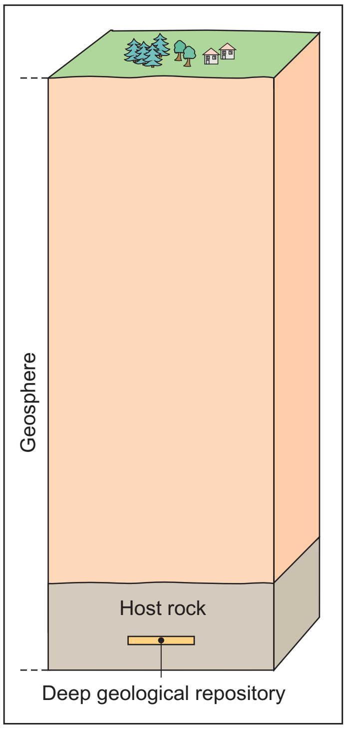


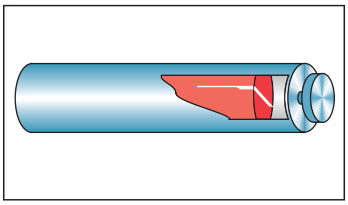
Fig. 2-6: The system of barriers for disposal of SF.

This figure corresponds to Figure 3-3a in Nagra (2008a).

Safety barrier system for HLW

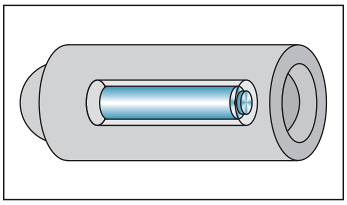
Waste matrix (glass)

- Fixation of radionuclides in the glass matrix
- Low glass corrosion rate



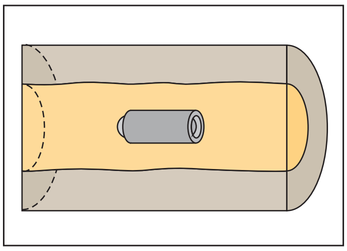
Disposal container

- Containment of the waste for several thousand years
- Thereafter: Restricted water inflow and retention of radionuclides (sorption on corrosion products)



Backfill (bentonite)

- Suitable interface between disposal containers and the host rock
- Favourable radionuclide retention properties
- Favourable conditions for long-term stability of the disposal containers



Host rock

- Low groundwater flux
- Favourable structure of the pore space
- Favourable geochemical conditions for radionuclide retention
- Favourable conditions for long-term stability of the engineered barriers

Geological situation

- Favourable host rock configuration for arrangement of the disposal tunnels
- Favourable conditions for long-term stability of the barrier system
- Absence of raw materials deposits that would be workable in the foreseeable future

Placement of disposal tunnels deep underground

- Isolation of the waste
- Prevention of unwanted access
- Protection from unintentional intrusion
- Protection from erosion

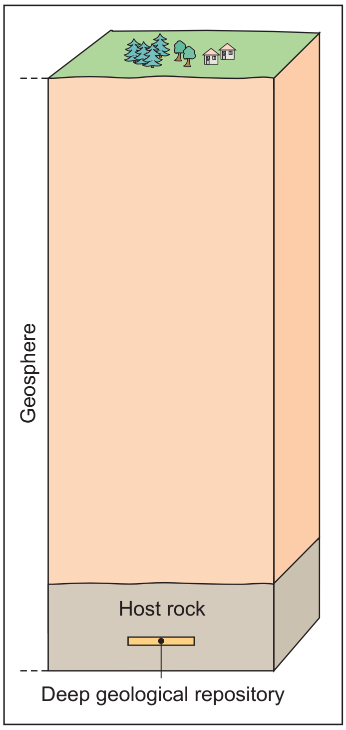


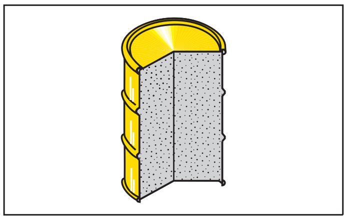
Fig. 2-7: The system of barriers for disposal of HLW.

This figure corresponds to Figure 3-3b in Nagra (2008a).

Safety barrier system for L/ILW

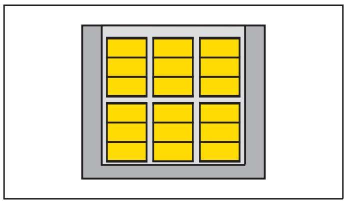
Waste matrix (various materials)

- Fixation of radionuclides in the waste matrix
- Slow degradation rate of the waste matrix



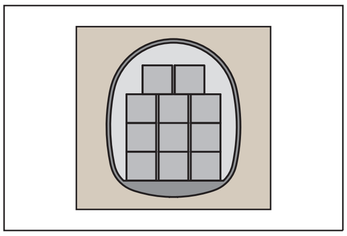
Disposal container

- Containment of the waste for a restricted time period
- Thereafter: Restricted water inflow and retention of radionuclides (sorption on container materials and corrosion products)



Backfill (cement mortar)

- Suitable interface between disposal containers and the host rock
- Favourable radionuclide retention properties
- Favourable conditions for long-term stability of the disposal containers



Host rock

- Low groundwater flux
- Favourable structure of the pore space
- Favourable geochemical conditions for radionuclide retention
- Favourable conditions for long-term stability of the engineered barriers

Geological situation

- Favourable host rock configuration for arrangement of the disposal caverns
- Favourable conditions for long-term stability of the barrier system
- Absence of raw materials deposits that would be workable in the foreseeable future

Placement of disposal caverns deep underground

- Isolation of the waste
- Prevention of unwanted access
- Protection from unintentional intrusion
- Protection from erosion

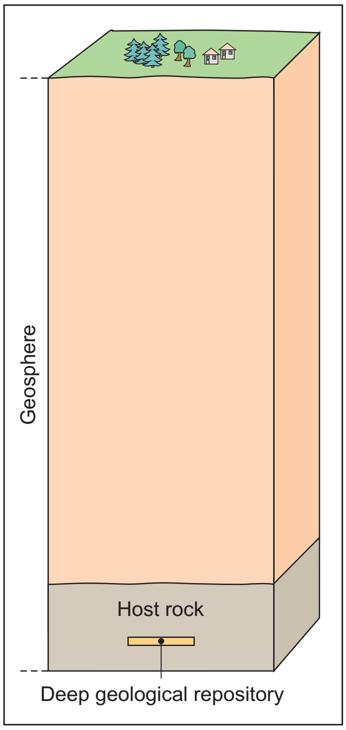


Fig. 2-8: The system of barriers for disposal of L/ILW.

This figure corresponds to Figure 3-9 in Nagra (2008a).

2.5 Nagra resources, URL facilities and associated competence centres

The means for implementation of the programme include the resources and facilities discussed below.

Nagra resources

Nagra is organised as a project management organisation and has a size of approximately 80 persons. Nagra is responsible for developing the disposal strategy in co-operation with its board of directors, develops the working programmes and manages the technical programme. Nagra staff develops key strategic issues (e.g. siting strategy, safety assessment methodology, geosyntheses, safety reports, waste inventories). Nagra is also responsible for communication with all interest groups.

URL facilities

There are two URLs in Switzerland, both of which are operated as international RD&D platforms with participation from many research organisations, national waste management organisations and regulatory agencies. The Mont Terri URL Project, operated by swisstopo (Swiss Federal Office of Topography), is in Opalinus Clay and is the location of most of Nagra's URL studies. One of the tunnels and the layout of the Mont Terri Underground Laboratory are shown in Figures 2-9 and 2-10. The latter also gives the location of ongoing and completed experiments. Nagra operates the URL at Grimsel (Fig. 2-11), where a wide range of research studies are also performed in cooperation with international partners. Various aspects of the URL studies are discussed in Chapter 6.

Fig. 2-9: One of the tunnels in the URL at Mont Terri: overcoring activities.

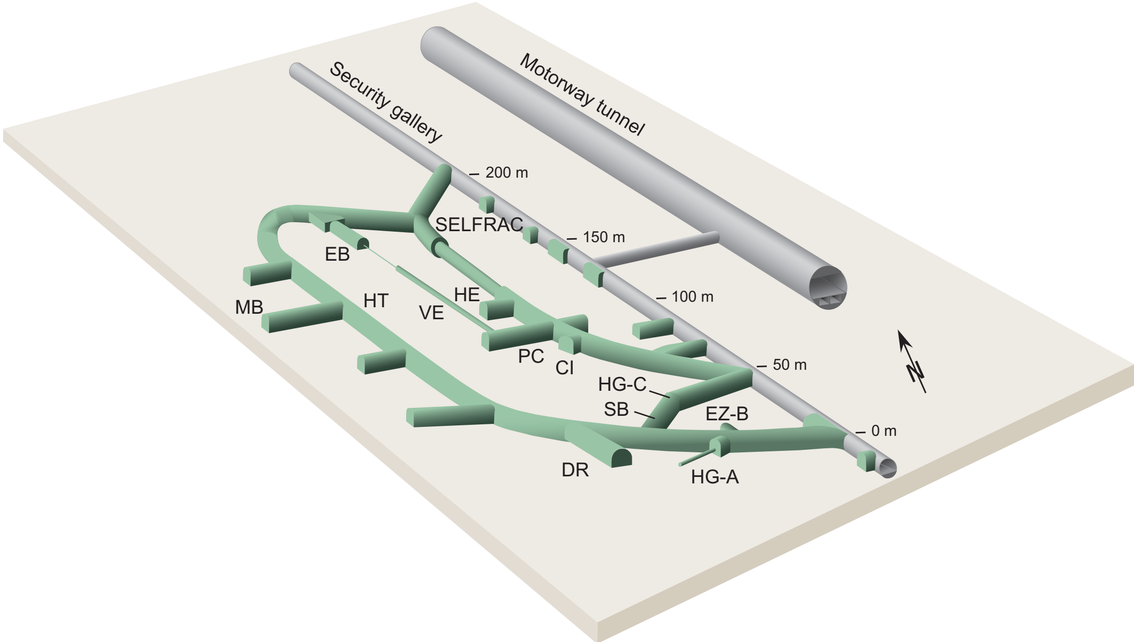


Fig. 2-10: The location of various experiments in the URL at Mont Terri. The experiments referred to are discussed in Chapter 6.

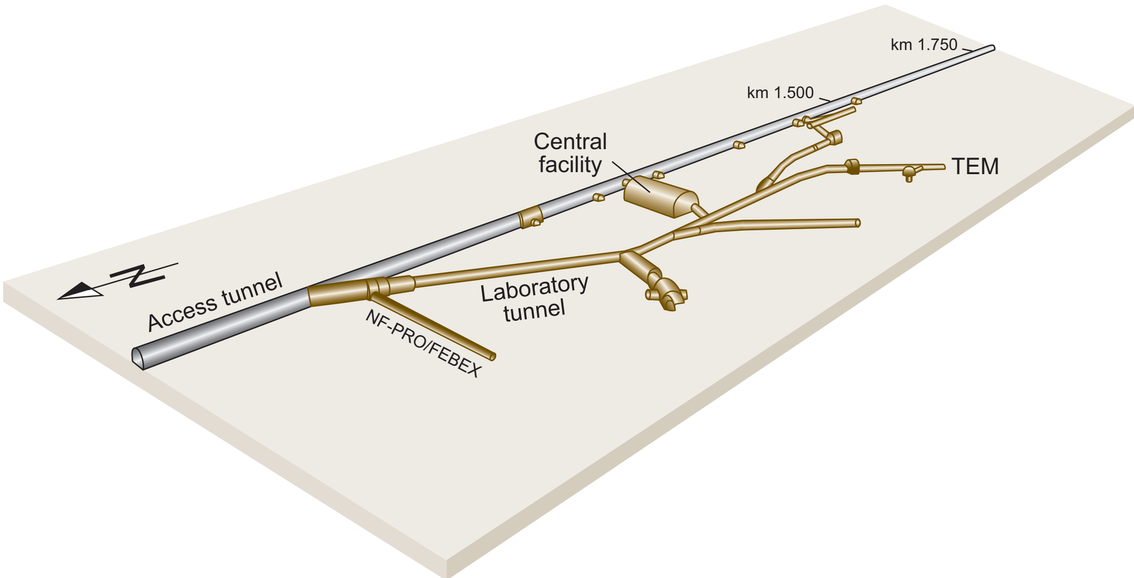


Fig. 2-11: The URL at Grimsel. The experiments referred to are discussed in Chapter 6.

Competence centres

Both the Paul Scherrer Institute (PSI) and the University of Berne have longstanding working relationships with Nagra and make important contributions to the scientific studies. These particular centres are noted because of their strong integration into Nagra's programme over a very long period of time and because of the uniqueness of their contributions. PSI also has shielded facilities and associated analytical expertise that can be utilised as required for detailed studies of various types of radioactive waste. The contributions of both PSI and the University of Berne to the planned RD&D work are described in Chapter 6, within the context of the various RD&D areas of work. Furthermore, a number of highly specialised small consulting companies having a longstanding involvement in Nagra's programme make vital contributions to Nagra's work.

3 The RD&D planning process and methodology

3.1 The RD&D planning process

The RD&D Plan is an integral part of the Nagra Quality Management System (QMS) and is one of the key elements of the strategic long-term planning of Nagra and of the Swiss waste producers.

The RD&D Plan provides input to:

- the annual budget process, by indicating the needs for resources in order to achieve specific goals
- estimates of the costs of implementing disposal, which are updated every five years as input to the financial planning by the utilities for the Waste Management Fund (funds for the disposal of radioactive waste) and the Decommissioning Fund (funds for decommissioning of nuclear power plants, see Nagra 2008a)
- the strategic planning of resources, including the human resources required by Nagra and by its RD&D platforms (i.e. underground laboratories) and competence centres (PSI and University of Berne) to carry out various RD&D activities
- decision-making by Nagra in relation to requirements for the various phases of repository development
- decision-making with respect to proposals for partner projects, by identifying areas in which participation in existing or potential European Union (EU) or other multilateral, bilateral or cooperative projects would be desirable, or areas where commercial work could provide experience that would also be valuable to repository projects in Switzerland
- identification of areas where explicit measures are needed to manage knowledge (Knowledge Management Process)

3.2 The RD&D planning methodology

A considerable amount of relevant technology, data and expertise already exists at Nagra and within other waste management organisations worldwide and further valuable information is available from the wider scientific and technical community and is documented in the corresponding literature. The challenge facing Nagra is to carry out RD&D in a manner that helps to deliver the projects at the required milestones, while making full use of relevant technology, data and expertise that are already available and monitoring relevant developments elsewhere. In doing so, Nagra should use its human and financial resources efficiently and share resources where appropriate. The methodology adopted to meet this challenge includes the following elements:

- establish a reference scenario for repository implementation up to the start of operation (Chapter 2.1)
- establish the strategic requirements associated with the various steps involved in planning, licensing and implementing the two types of repositories foreseen in Switzerland (discussed below and in Chapter 5)
- use the broad planning assumptions and strategic requirements to set the overall RD&D priorities

- assess the current status of RD&D in Switzerland and worldwide and identify any gaps that will need to be addressed in meeting the strategic requirements for the future licensing stages (i.e. outstanding issues and uncertainties, which are based on findings from Nagra studies and from recommendations given in formal reviews of Nagra proposals) (Chapters 4 and 5)
- plan the specific work to be carried out to address each particular issue; the broad outline over the various stages of repository development in the various areas is given in Chapter 5, with more detail provided in Chapter 6 for the period up to the general licence application

3.2.1 Management of requirements for repository development

The requirements for the programme for repository development are discussed here, taking into account the diverse sources and their impacts on the programme at various levels, including repository concept development and timing of the various steps of implementation. These aspects are being evaluated and tracked within Nagra using a Requirements Management system, which is in the development stage. The overall framework for managing requirements is discussed below.

The requirements that drive the programme for repository implementation can be categorised in the context of addressing four basic questions:

- **What is the origin of the requirement?** Nagra considers that they arise from five different broad categories:
  - legal, regulatory and policy requirements
  - shareholders (waste producers) needs
  - technical programme (science and technology) requirements as assessed by Nagra
  - authorities' recommendations
  - expectations from the scientific community and the public
- **What is the nature of the requirement?** In this context requirements can be placed in a hierarchy, from qualitative strategic and functional at the highest level down to detailed specifications at the lowest level; of necessity, lower level requirements must satisfy the requirements stated at levels above.
- **What element does the requirement apply to?** This also has a hierarchical context, with the waste management concept at the highest level, the repository concept and engineered barriers concept and detailed design at lower levels.
- **When and at what level of detail must compliance with the requirement be reached?** This recognises that repository implementation occurs over decades and that there are progressive stages of development and maturity for the various elements.

These aspects are elaborated below. An overview of the strategic requirements for repository development is given in Chapter 5.

Origin of requirements

The requirements related to repository development originate from five broad categories:

- **Legal requirements, regulations and policy requirements** – The legal requirements in the Nuclear Energy Act (KEG 2003) and the Nuclear Energy Ordinance (KEV 2004) define the overall requirements for obtaining licences for the various steps shown in Figures 2-1 and 2-2. The licensing steps and the required documentation are summarised in Appendix 1. The radiological safety objectives for disposal of radioactive waste are specified in G03 (ENSI 2009), replacing HSK-R-21 (HSK & KSA 1993). The Nuclear Energy Act requires disposal of all wastes in geological repositories, which must be monitored for a certain time before closure. Important elements that must be incorporated into the repository design include the *test facility*, which would be constructed in the early stages of underground exploration at the final disposal site, and the *pilot facility*, where a small quantity of waste would be emplaced in order to monitor relevant parameters under repository conditions and the *main facility* that contains the majority of wastes and that will be backfilled and sealed as soon as waste emplacement is completed. With the pilot facility and the requirement for the possibility of retrieval without great effort, opportunities are provided for review and possible reversal of decisions, including the retrieval of emplaced wastes. The Sectoral Plan for Geological Repositories (FOE 2008) defines the steps leading up to selection of a site for which a general licence application will be prepared.

- **Requirements of the waste producers** – These establish the timing, composition and volumes of wastes that need to be dealt with. The projected waste arisings from the existing nuclear power plants with an operation time of 50 years are given in Table 2-1. An overall bounding waste volume that includes reserves for new nuclear power plants and a prolonged period of collecting MIR wastes also needs to be taken into consideration for repository planning. For all radioactive wastes produced up to date and in the future, Nagra has established formal waste acceptance requirements that must be met by waste producers.

- **Requirements from science and technology** – These represent the need to develop the science, technology and safety basis for repository implementation, which involves Nagra's evaluation of the knowledge base in the various areas as well as planning of the appropriate timing of various developments. Clearly, this evaluation must also involve the consideration of the other categories of requirements. Technical requirements are derived by Nagra, based on evaluation of the other requirements and on experience in developing disposal programmes and preparing safety cases, including reviews of Nagra projects by the authorities, and based on the status of and the expected technical developments in projects worldwide. Included are requirements related to site characterisation, technology development and demonstration, operational safety and long-term safety.

  Operation of the HLW repository will not start until 2040 – 2050. As a result, many technological developments will have taken place in other projects, and in technology in general, that may have the potential to be adopted by Nagra, in particular in relation to engineered barrier system design and construction and repository engineering (including waste emplacement technology). These would include many full-scale demonstrations of relevant technologies in other programmes.

  The concept of demonstration exists at several levels in the context of repository development. The first could be described as demonstration of the feasibility of key technological elements. An example in Nagra's RD&D programme involves studies of emplacement of pelletised bentonite at large-scale, which have been pursued at Mont Terri and elsewhere. The next level involves demonstration that full-scale components can be manufactured (e.g.

the SKB copper canister; SKB 2006a). The final level involves demonstration of integrated operations at full-scale (e.g. the requirement that Nagra demonstrate canister retrievability prior to receiving the nuclear operation licence for the repository).

For the next ~ 10 years, Nagra's RD&D strategy in the context of the time plan for implementation focuses on the siting issues and on the feasibility of key technological elements, because key technical aspects that are decisive in relation to judging feasibility and long-term safety (demonstration of the fundamental technological principles) must have a secure foundation for the stage of the general licence application. The demonstration requirements for the succeeding stages of repository development will be pursued on an "as early as necessary and as late as possible" basis to take advantage of external developments in technology (see Fig. 4-1 and 4-2) and to optimise use of resources. A detailed discussion of demonstration of the necessary technologies in this context is given in Chapter 6 for the various RD&D areas.

- **Requirements arising from recommendations of the authorities** – These relate to requests and recommendations of the authorities, which arise through formal reviews of projects and through other interactions. Nagra's projects such as Project Entsorgungsnachweis for the HLW repository and the Wellenberg general licence application were formally reviewed by the authorities and the recommendations have been carefully evaluated by Nagra. The studies to address these issues are incorporated into RD&D planning, in order to resolve these issues at subsequent steps of repository development. The recommendations from the review of Project Entsorgungsnachweis and the manner of dealing with the recommendations are discussed in Nagra (2008b). The studies that address many of these recommendations are discussed in the programme of work in Chapter 6.
- **Requirements arising as a result of expectations from the scientific community and the public** – Included in this category are the expectations of external scientific experts and expectations arising from input during public consultation, e.g. during the Sectoral Plan process.

Implementation framework

The requirements are evaluated in the context of a hierarchy for developing the repository design concepts, considering aspects related to both the function and level of detail required and to the timing of implementation of the repository. This is illustrated in Figure 3-1. Here the Nagra evaluation of technical programme requirements incorporates evaluation of the various other categories of requirements. These result in *system requirements*, i.e. safety and design principles that should be satisfied (see Nagra 2002c, 2008e). Below this are *concept design requirements*, i.e. the repository concepts for the different waste types (see Figs. 2-5, 2-6 and 2-7). For these concepts, there are *functional requirements* (e.g. containment of HLW for at least 1000 years) and criteria through which they are evaluated (e.g. corrosion rate of the canister vs. required wall thickness). Below this are the *sub-system design requirements*, i.e. the materials and associated characteristics that meet the functional requirements. Finally, there is the *verified design*, which shows that the system or component functions according to the purpose.

The implementation framework in Figure 3-1 also shows that time until repository implementation is also an important consideration, as details of the *system design* and *verification of the design* are progressively further developed as the programme proceeds.

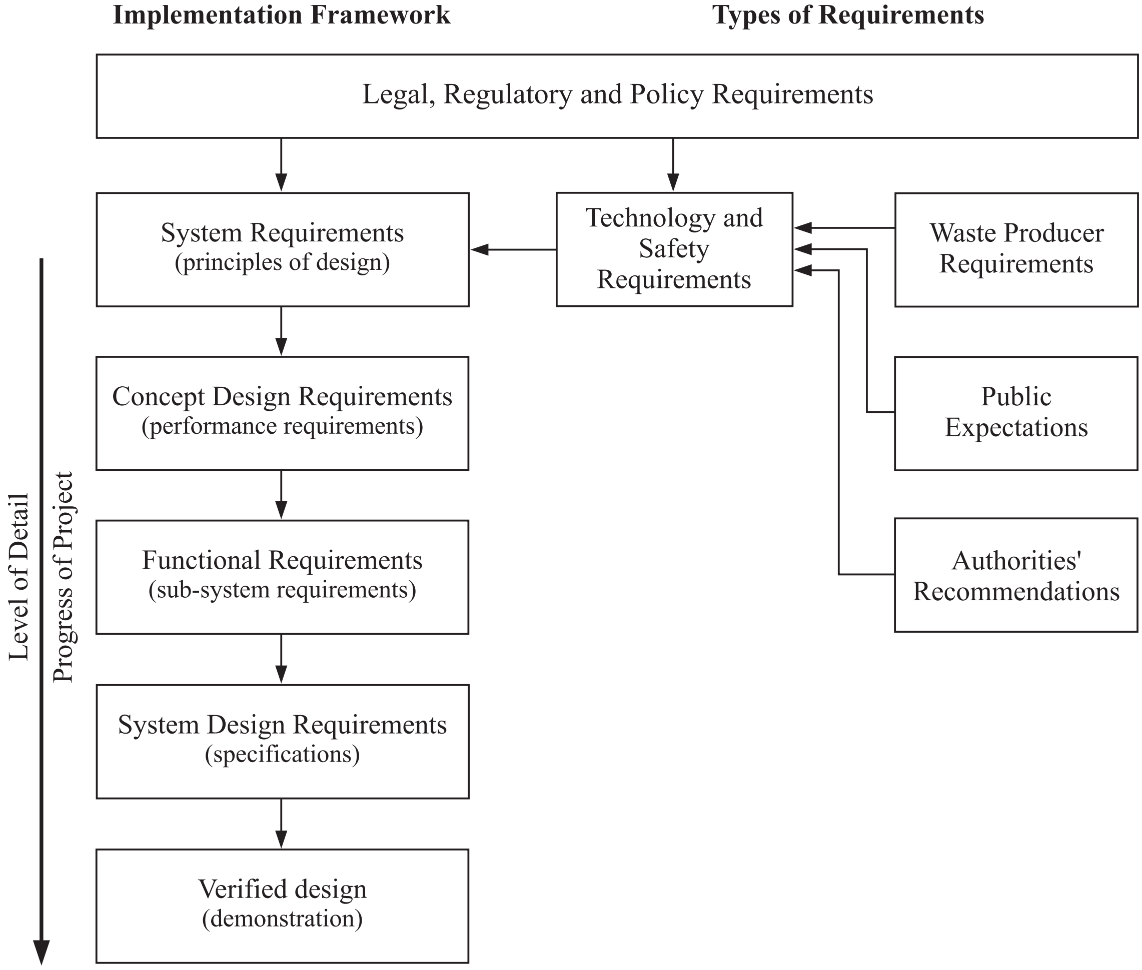


Fig. 3-1: Simplified scheme of the management of requirements for repository implementation.

The level of detail associated with the requirements will increase with progress in repository planning.

3.2.2 Approaches for addressing RD&D requirements

The general approaches available for addressing the RD&D requirements identified by the above methodology are summarised in Table 3-1, which also indicates the types of issues for which a particular approach might be appropriate.

The approach adopted can depend on a number of factors, including:

- the priority assigned to an issue, which may be related to the time at which the information is required as well as its significance and the challenges involved in achieving the required results
- the degree to which full project control over the work related to an issue is required
- the need to maintain core competency at Nagra in areas of siting strategy and safety methodology and the requirement for Nagra staff to present and explain the results to the authorities, elected representatives and the public

- the need to maintain or develop scientific and engineering competence in particular areas at Nagra and at the competence centres, and the opportunities to resolve some issues because strong scientific competences already exist in certain areas
- the possibility to learn from others and to limit the duplication of work
- cost effectiveness

Tab. 3-1: The approaches available for resolving outstanding issues and uncertainties.

Possible approaches		**Issues for which the approach may be appropriate**
A	To carry out RD&D projects relying on Nagra staff at a technical as well as managerial level.	Appropriate for high-level strategic and methodological issues (siting strategy, safety strategy, safety assessment methodology, strategy for URL studies) and technical areas requiring expertise specific to the Swiss programme (e.g. producing the overall syntheses for geoscience, engineering projects and safety; waste inventory definition and associated characteristics).
B	To manage RD&D projects for which technical work is undertaken by competence centres external to Nagra	Appropriate if the approaches below (C, E) are unavailable or inadequate, or if the option of "buying in" knowledge (D) is rejected because of a desire to maintain or develop competence in particular areas at the competence centres (e.g. PSI and University of Berne). An important consideration is the availability of national competence centres. Nagra's management role is confined to the strategic level (definition of work programme areas and requirements), which enhances Nagra's multi-disciplinary overview.
C	To engage in partner or commercial projects	Appropriate (and cost-effective) for issues requiring RD&D that are of common interest to other organisations, because know-how and knowledge can be pooled. Such projects also enhance acceptance and credibility.
D	To "buy in" technology, data and expertise from outside	Appropriate (and cost-effective) where, for example, site characterisation techniques, computer codes, etc. are known to exist, but are not currently available to Nagra, especially if there is no need to develop detailed technical competence in these areas, or if there is uncertainty as to whether Nagra RD&D would deliver the required product in time for the next project milestone. This nevertheless requires the capabilities at Nagra to manage such projects.
Possible approaches		**Issues for which the approach may be appropriate**
E	To monitor developments internationally	International developments will of course be monitored in all relevant areas. It may, however, be the *sole* approach, if: - no RD&D requirements are identified in the assessment of current status (such aspects are not dealt with in the RD&D plan) - an issue is judged to be of low priority for the next milestones - adequate work is being carried out already by other organisations and will be available in the public domain in time for the relevant milestone This nevertheless requires the capabilities at Nagra to oversee the relevant scientific-technological area of work

4 Status of RD&D for disposal of HLW and L/ILW

4.1 Introduction

The present situation regarding the process for selection of suitable potential sites for disposal of HLW and L/ILW in Switzerland and the subsequent application for general licences is the culmination of a series of technical and scientific studies and political decisions over a period of about 30 years, as discussed in Chapter 1.2. Here the principal underlying technical and scientific considerations related to the decisions are discussed. The concept for a HLW repository (with the preferred host rock option Opalinus Clay) is summarised, along with a brief discussion of the future RD&D priorities identified by Nagra in performing Project Entsorgungsnachweis. A summary of the main recommendations of the authorities' reviews of the project is also provided; these reviews identified outstanding issues and uncertainties that should be resolved in the course of future project stages. The priority RD&D issues for development of a L/ILW repository in Switzerland are also noted based on experience with the Wellenberg project and elsewhere. In addition, some of the technological developments that have been made in other national disposal programmes are briefly reviewed. Because several of these programmes are planning to implement SF or HLW repositories within the next 15 – 20 years, these developments are particularly relevant to the Swiss programme, with its implementation date for the HLW repository of 2040 to 2050.

4.2 Status of RD&D for development of HLW and L/ILW repositories in Switzerland

4.2.1 The HLW programme and RD&D priorities

4.2.1.1 Background

The current status of work in the HLW programme is largely the result of work done to meet existing requirements and recommendations of the Swiss authorities following the review of studies that preceded Project Entsorgungsnachweis (Project Gewähr, Kristallin-I). An important milestone was Project Gewähr (Nagra 1985), which addressed construction and siting feasibility and long-term safety of a repository for HLW in the crystalline basement of northern Switzerland.

In its decision on Project Gewähr, which was handed down in 1988, the Federal Government judged that two out of three conditions for the demonstration of overall disposal feasibility for HLW were satisfied, i.e.:

- construction feasibility was demonstrated; safe construction and operation are possible with current technologies
- long-term safety was shown to be achievable, provided that the database used in the analyses could be confirmed to be applicable to a sufficiently extensive potential disposal area
- the highly localised nature of the geological field data for the crystalline basement did not, however, allow one to say with confidence that sufficiently large blocks of crystalline rock with the required properties could be found in Switzerland; a suitable site could not be shown to exist on the basis of available information and thus siting feasibility was not fully demonstrated

The government required that siting feasibility be more convincingly demonstrated and also that sediments be investigated more intensively as alternative potential host rocks for the disposal of HLW. Nagra subsequently expanded the geological investigations, construction feasibility studies and safety studies of sedimentary host-rock options in parallel with its work on crystalline rock.

In the late 1980's, Nagra documented results from investigations of sedimentary rocks in northern Switzerland (Nagra 1988, 1991) and in a subsequent review Nagra proposed the Opalinus Clay as the favoured sedimentary rock option (Nagra 1994c) and this was confirmed by the authorities (HSK 2002). The Lower Freshwater Molasse (USM) – which was also considered as a potential host rock – became a reserve option due to its heterogeneity and corresponding poorer barrier performance and the inherent difficulties for its characterisation.

The additional crystalline field investigation studies were incorporated in the synthesis Kristallin-I (1994), in which Nagra concluded that a repository in crystalline rock in northern Switzerland would be feasible from a long-term safety perspective, although considerable work would be required for identification and detailed characterisation of potential sites and on repository layout and EBS design aspects.

In their review of Kristallin-I, HSK (2004) maintained their reservations regarding the chances of finding blocks of rock for a repository of sufficient size with adequate properties. The concern is related to the strong tectonisation of the rock, which may lead to insufficient size of blocks with adequate qualities for a suitable repository layout. In Nagra's view, the negative impacts of associated disturbances (e.g. highly conductive fracture zones) may be possible to overcome with an alternative barrier concept (e.g. very long-lived copper canisters). Nonetheless, the necessity for a large number of boreholes and a shaft with exploratory tunnels in order to develop information for a more reliable assessment of crystalline rock makes the pursuit of further field studies questionable, especially in light of the strong consensus that Opalinus Clay has suitable characteristics for a repository.

4.2.1.2 Project Entsorgungsnachweis and RD&D identified therein

Nagra submitted Project Entsorgungsnachweis to the Federal Government for review in December 2002. This project, which is based on the Opalinus Clay host rock option and on the potential siting region in the Zürcher Weinland, was an important milestone in the programme for disposal of HLW. The principal emphasis was on demonstrating that a site with suitable characteristics exists and can be characterised, and that, based on its properties, safety and engineering feasibility could be demonstrated.

The design concept, geosynthesis and safety assessment for a HLW repository in Opalinus Clay were presented in Nagra (2002a, b, c). The safety strategy and repository layout concept are described and illustrated in Chapter 2.4.

A study such as Project Entsorgungsnachweis provides a valuable platform for discussion of the future programme, as the detailed syntheses of the various areas of science and the safety analysis derived from them provide insights into the technology, data and expertise that must be developed for the next programme phase. In chapter 8.4 of Nagra (2002c) Nagra identified a range of issues that are being addressed in on-going and planned studies, including:

- diffusion experiments in Opalinus Clay at Mont Terri and in the laboratory using a variety of radionuclides

- investigations of self-sealing of fractures within the excavation-disturbed zone of the tunnel and in other locations
- a heater experiment at Mont Terri to enhance system understanding of the bentonite and rock associated with the transient phase when temperatures are enhanced
- studies on Opalinus Clay deformation mechanisms to enhance system understanding
- studies at Mont Terri on the transient behaviour of the host rock during saturation and desaturation as well as the interaction of the Opalinus Clay with the bentonite buffer
- investigations regarding the practicalities of using bentonite granules to fill repository tunnels
- additional experiments looking at gas release through the host rock and seals

As noted in Chapter 6, these issues continue to be studied along with many other issues arising from the review and from the natural evolution of ongoing studies.

4.2.1.3 RD&D issues identified in the reviews of Project Entsorgungsnachweis

In September 2005, the extensive reviews by HSK (HSK 2005), KNE (KNE 2005), KSA (KSA 2005), and NEA (NEA 2004), on Project Entsorgungsnachweis became available to the public. They all came to positive conclusions and HSK recommended to the Federal Government to accept the demonstration of disposal feasibility. However, a large number of recommendations were made regarding studies that should be performed in relation to future development stages. In June 2006, the Federal Government decided that Nagra had successfully shown that disposal of SF/HLW and ILW in Switzerland is technically feasible. The Federal Government, however, asked for a report that would describe how Nagra plans to deal with the numerous issues raised in the reviews of project Entsorgungsnachweis.

The most significant of the ~ 200 recommendations from these reviews are summarised below (in alphabetical order according to the reviewer). The complete list of recommendations is documented in Nagra (2008b), which also provides comments on how these issues are being addressed in the context of the time plan for repository implementation. In the present report, the studies that deal with the authorities' recommendations are discussed in the context of the complete programme of work in Chapter 6.

Key Recommendations of HSK

In their review of Project Entsorgungsnachweis, HSK identified a large number of recommendations and open questions that should be addressed in future stages of the SF/HLW/ILW disposal programme and clarified in the event of continuation of the Opalinus Clay Project in the Zürcher Weinland region (HSK 2005). In their view, the most important of these relate to the safety of the future repository:

- The technology for inspecting the integrity of final closure seal of the loaded canisters, the mechanical stability of the SF canisters, the impacts of corrosion-induced volume increases and the potential for stronger sulphide corrosion of the steel canisters.
- The behaviour of the bentonite as a consequence of high temperatures, gas breakthrough effects and the material properties of granular bentonite.
- The processes leading to gas generation in the repository and, more importantly, to gas transport through the bentonite or cement backfill and through the Opalinus Clay.

Further recommendations relate to the siting demonstration and the demonstration of engineering feasibility; these can be summarised as follows:

- Siting demonstration:
  - The confining units above and below the Opalinus Clay should be characterised in more detail to allow the containment potential of these strata to be quantified.
  - The hydrogeological dataset should be expanded and confirmed and should, in particular, include the confining units.
  - Glacial gully erosion processes should be clarified in greater depth so that potential future impacts can be better bounded.
- Demonstration of engineering feasibility:
  - To facilitate water drainage and ventilation, it would be of advantage to connect the access tunnel with the ventilation and construction shaft at different depths.
  - The tunnel and shaft cross-sections should be optimised based on required operational clearances, alignment of structures, construction procedures and expected convergence.
  - In terms of construction procedures, clarification is required of the appropriateness of the raise boring technique, water drainage, use of a tunnel boring machine and measures to secure the excavated tunnels.
  - The design of the ventilation system should be optimised, particularly for the third stage of construction when a lot of heat has to be removed.
  - The analysis of potential underground hazardous events and measures to be taken against these should be refined.

Key recommendations of KSA (Federal Commission for Nuclear Safety)

In their review of Project Entsorgungsnachweis (KSA 2005), KSA made the following recommendations for future stages of the SF/HLW/ILW programme:

- Once a site has been selected, the barrier function of the confining units should be investigated in more detail and also considered in the safety analysis for the reference case.
- Once a site has been selected, the robustness of the deep geological disposal system in terms of meeting Protection Objective 1 of the HSK R-21 Guideline should be investigated systematically in greater depth by analysing additional cases.
- To avoid the barrier function of the Opalinus Clay being compromised by gas production due to corrosion of the steel canisters, alternative canister materials and/or concepts should be evaluated. The effects of increased gas pressures and temperatures over long period of time on the transport properties of the Opalinus Clay and the bentonite should also be investigated. The gas issue should be considered in an integrated manner.
- The feasibility of a self-sealing structure should be clarified in a specific study.
- Minimum requirements and design criteria should be specified for the individual barriers.
- During the operation of nuclear power plants and the treatment and conditioning of the wastes, more attention should be paid to meeting the needs of waste management including those of deep geological disposal. For SF and HLW, this applies particularly to the layout of the core and specification of maximum burnup; for ILW it applies to the content of organic substances.

- A monitoring concept should be prepared for the pilot facility and targeted research and development should continue on the use of suitable measurement systems that are stable in the long term.
- Requirements for the stability and permeability of sealing structures should be quantified and documented in implementation specifications.
- The retrievability study should look in more detail at the reliability and ease of repair of the automatic excavation equipment under the expected conditions, as well as any surface facilities that may be required in the event of retrieval.
- Nagra should follow up the questions and recommendations and the identified needs for further R&D highlighted in the reviews by HSK, KNE, NEA-IRT and KSA in an RD&D programme that accompanies the waste management programme as specified in Article 32 of the Nuclear Energy Act and Article 52 of the Nuclear Energy Ordinance. This should include, in particular, the question of the materials to be used for the disposal canisters.

In terms of fundamental aspects of future work in the radioactive waste management programme, KSA also made the following recommendations:

- In parallel with the waste management programme to be submitted by the waste producers, an RD&D programme should be established and regularly reviewed and adapted to the current state of science and technology. It should also include social science studies and projects.
- The idea of a Waste Management Advisory Board should be implemented by the Federal Government as quickly as possible.
- Nagra should follow relevant IAEA's recommendations and bring its quality management system into line with ISO 9004:2000, as well as continually modify the system to meet the requirements of the particular stage of the waste management programme.

  Nagra should also establish a permanent group of independent experts to review the quality, completeness and traceability of its activities, as well as the strategic orientation of its work.
- All important affected stakeholders should be involved in procedural steps leading to implementation of deep geological disposal, particularly in the site selection process that follows the demonstration of disposal feasibility. This should be done within the framework of an organised participatory process that is in accordance with current practice.
- The knowledge and data from research and development conducted by Nagra and other involved organisations and authorities should be brought together by Nagra in a comprehensive databank. Nagra's quality management system should also include a process addressing knowledge management.
- Nagra and the authorities should – already at the present stage – be actively conducting research on how to best pass on information on a closed geological repository to future generations.

Key Recommendations of KNE (Commission on Nuclear Waste Management)

KNE (KNE 2005) raised a number of issues in the following main areas that were recommended for further consideration in the future, including:

- Further development of the geodynamic concept.
- Further clarification of processes occurring during glacial gully erosion.

- Investigation of the small increase in the permeability of tectonic discontinuities at a depth of 600 m (self-sealing capacity of the Opalinus Clay).
- Continuing the investigations of geochemical immobilisation of radionuclides (thermodynamic datasets, sorption processes, influence of hydrogen gas on chemical reaction processes, evolution of the cement system with time).
- More detailed investigation of the properties and behaviour of the bentonite barrier and processes at the bentonite/host rock interface in the context of heat production by SF and HLW (including hydromechanically coupled processes in the near-field).
- Optimising the design of the repository (alignment of the access tunnel, tunnel and shaft cross-sections, also taking into account conditions in the construction phase).

OECD/NEA Review of the Safety Case

A scientific review of the safety case of Project Entsorgungsnachweis was carried out by an International Review Team (IRT) under the auspices of the Nuclear Energy Agency (NEA) of the OECD (NEA 2004). The most important recommendations from the perspective of short- and medium-term RD&D planning are:

- Studies of the high-temperature behaviour of bentonite (particularly the pellets proposed for use) and of the thermo-hydro-mechanical aspects of the near-field should be continued.
- Investigations of radionuclide retention in clay systems (bentonite, Opalinus Clay) should be continued.
- Further surface-based site investigations (confining units, clarification of other aspects) should be carried out if the Opalinus Clay of the Zürcher Weinland continues to be considered as an option.
- Safety analysis methodologies and associated calculation tools should be further developed.
- Experiments on gas transport processes should be continued, including field and laboratory tests and modelling studies.
- Copper should be retained as an option for SF and HLW disposal canisters.

As noted earlier, the responses to all these recommendations are outlined in Nagra (2008b) [9].

4.2.1.4 Siting options for the HLW repository

In the course of the review of Project Entsorgungsnachweis, the Federal Government requested Nagra to prepare a report on siting options for the HLW repository. In this report (Nagra 2005) the Opalinus Clay was confirmed as the preferred host rock option with the crystalline basement of northern Switzerland and the Lower Freshwater Molasse (USM) being reserve options. Furthermore, for the Opalinus Clay several broad regions were identified that offer siting possibilities for the HLW repository.

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[9] Nagra (2008b) is available only in German, but the studies arising from the recommendations of the reviews by the authorities are discussed in Chapter 6 in the context of the relevant programme areas.

4.2.1.5 Proposed siting regions (Stage 1 of Sectoral Plan)

For the HLW repository, Opalinus Clay has been identified as the preferred host rock. The identified siting regions are 'Zürcher Weinland', 'Nördlich Lägeren' and 'Bözberg'. More details are given in Section 5.3.2.

4.2.2 The L/ILW programme and RD&D priorities

4.2.2.1 Background

Site selection started in the early 1980s and identified in a first step one hundred sites, that were then first reduced to twenty and then to three sites to which at a later stage a fourth site was added. At these four sites field investigations were made. In 1993 the site of Wellenberg was selected as the site for implementation and in 1994 a general licence application submitted. After two votes by the Canton of Nidwalden rejecting the concession for using the underground, the project was discontinued in 2002.

4.2.2.2 Wellenberg programme

A general licence application for a repository for L/ILW at Wellenberg was submitted in 1994 (GNW 1994) and was favourably reviewed by the authorities in 1996 (HSK 1996). A number of recommendations were made and these have been evaluated. The design aspects and safety analysis approaches are considered relatively mature, although the gas production and transport issues require further development.

As a result of discontinuing the project at Wellenberg after the second negative cantonal referendum of 22 September 2002 and the establishment of the Sectoral Plan process, Nagra has again evaluated potential siting regions for a repository for L/ILW. Taking advantage of the technical progress since the early 1980s (e.g. the possibility of moving heavy containers downwards through a shaft / ramp), the sites now considered are no longer restricted to those with horizontal access. Nagra has proposed several potential host rocks (Opalinus Clay, 'Brauner Dogger', Effingen Beds, Helvetic marls; see Section 5.3.2). The design options include selection of a separate disposal site for this waste category, as well as co-disposal at the same site as for disposal of HLW.

4.2.2.3 Proposed siting regions (Stage 1 of Sectoral Plan)

Information regarding the L/ILW potential host rocks and siting regions is given in Section 5.3.2.

4.2.2.4 RD&D priorities identified

RD&D studies for L/ILW overlap with those related to the engineered barrier system for long-lived ILW, i.e. waste characteristics, gas generation and release, and radionuclide retention in the cementitious materials used to condition the wastes and backfill the disposal containers and the waste emplacement tunnels. Although the range of potential host rocks identified for L/ILW is broader than for the HLW programme, much of the information developed in the HLW programme can also be directly applied for aspects related to radionuclide retention in the host rocks other than Opalinus Clay[10], although specific laboratory studies will be commissioned. Furthermore, the L/ILW programme can profit from the experience in the HLW programme regarding gas transport in host rocks. Finally, the work done in the Wellenberg programme is directly applicable to the Helvetic marls but is also relevant for the Effingen Beds.

4.3 Worldwide status of RD&D for disposal of SF/HLW/ILW and L/ILW and expected future developments

4.3.1 The Swiss schedule for repository implementation in a worldwide context

The RD&D studies of Nagra's programme can take advantage of the developments in other countries, in particular because these developments in many cases precede those in Switzerland. Schedules for implementation of deep geological repositories for L/ILW and for alpha-toxic or long-lived intermediate level waste in a number of countries are given in Figure 4-1. Near surface disposal facilities for LLW, of which many are in operation worldwide, are not included although relevant information is also available for these repositories.

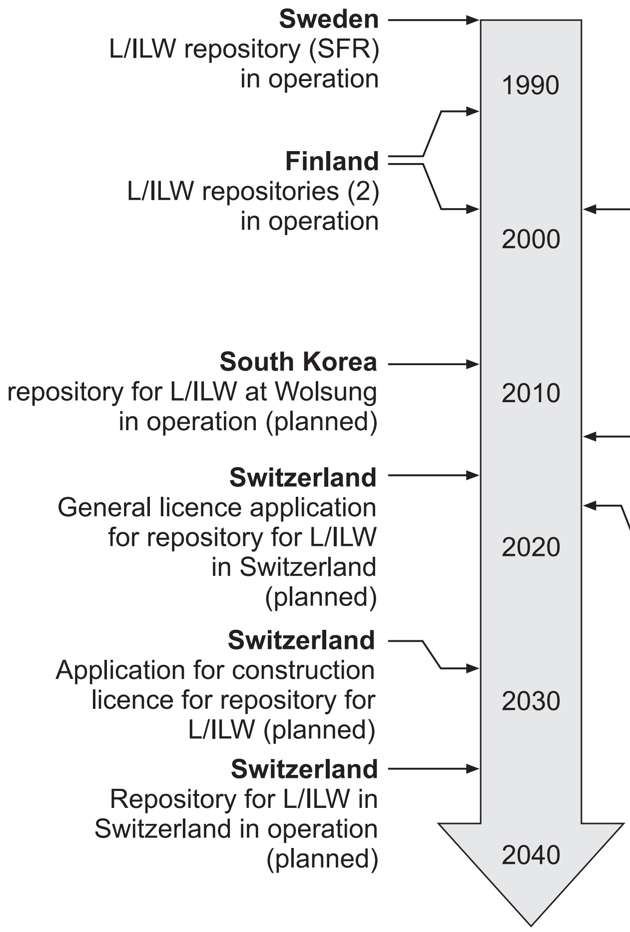

Fig. 4-1: Comparison of some key milestones for development of geological repositories for L/ILW in several countries.

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10 The clay-rich sequences of host rock 'Brauner Dogger' proposed for the L/ILW repository are very similar to the Opalinus Clay.

A similar comparison for HLW repository implementation is given in Figure 4-2. The summaries in both cases are not comprehensive, but are intended to draw attention to the developments in other countries that significantly precede those in Switzerland. The significance of this is that it is reasonable to assume that there are and will be many relevant technical developments in these projects that may be expected to enhance the diversity and knowledge base of proven options available to deal with various safety, design and technical development issues in the Swiss programme. Some specific examples that are particularly relevant are discussed in the following section.

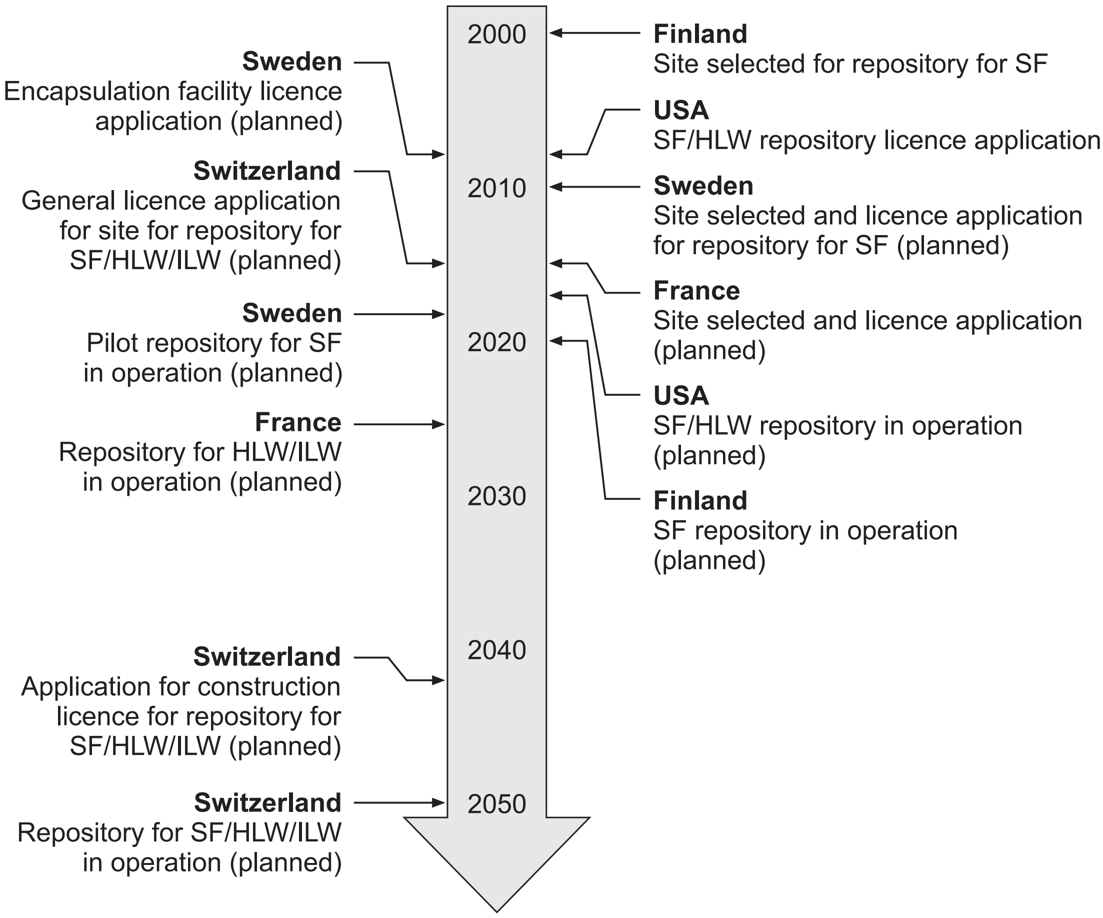


Fig. 4-2: Comparison of some key milestones for development of geological repositories for SF/HLW in several countries.

4.3.2 Important worldwide technical developments and their potential impacts on Nagra's RD&D programme

Some important technical developments that have taken place, or can be expected to occur within the next 15 to 20 years, are discussed here under the categories of main components of the disposal system. The focus here is on technological developments, because advanced schedules for repository implementation exist in several countries, which may permit Nagra with its later implementation dates to evaluate the technical developments in these programmes prior to narrowing down of the technological options and making its own significant investments in technology development. Provided that the fundamentals of the various technologies are demonstrated, there is considered to be no requirement to perform full-scale technological demonstration of the various technologies (e.g. fabrication of disposal canister prototypes, emplacement of disposal canisters and backfill and retrieval of disposal canisters) until after the general licence application. The status of technology development work in other countries and its relationship to Nagra's needs is discussed below.

In contrast to technology development aspects, Nagra is presently active in all other relevant research areas either directly, through its competence centres or through international collaboration. These aspects are discussed in Chapter 6.

Technology for disposal canisters for SF and HLW

In Sweden and Finland, the technology for copper canister fabrication is fully developed and many prototype canisters have been produced. The applications for construction of encapsulation facilities in Sweden and in Finland are expected to be made in 2010 and 2015 respectively (SKB 2007a, Posiva 2006). Pilot repository operation in Sweden is scheduled to begin in 2020 and in 2020 – 2025 in Finland. Even if some delays occur, it can reasonably be expected that all licensing, manufacturing and production issues for the copper canisters will be resolved well before Nagra needs to make a final choice of canister material and production technology (~ 2030, see Chapter 6).

In France, work is proceeding for design and production of carbon steel canisters for disposal of HLW glass, but other options are also being looked at (e.g. ceramics). The application for a disposal facility construction licence is expected in 2015 and the planned date for operation of the repository is 2025. It is thus expected that canister manufacturing issues will be resolved within the next 15 to 20 years.

Technology for bentonite buffer material fabrication and emplacement

In the planned Nagra approach for buffer and SF/HLW canister emplacement, the canister would be brought into position on bentonite blocks, with the space around the canisters subsequently filled with highly compacted granular bentonite. Sweden and Finland have considerable experience with fabrication of full-scale buffer blocks and a buffer fabrication facility has recently been built at the Äspö laboratory. There is a high degree of confidence in the present-day technology for block production and emplacement (see SKB 2007a). As discussed in Chapter 6, Nagra is focusing in particular on granular bentonite pellet production and emplacement technology, which has been studied less in other countries and is the preferred emplacement concept for a repository in Opalinus Clay. As a result, development of granular bentonite pellet production and emplacement technology is being intensively studied so as to ensure that the required density, homogeneity and properties can be achieved (see Section 6.5.3.3.2).

Tunnelling and tunnel support technology for deep claystone formations

It is expected that some benefit will come from following experience in deep tunnelling projects, including studies performed in the Meuse-Haute-Marne URL of ANDRA in Callovo-Oxfordian Clay. Despite the knowledge gained from other sites, it is apparent that the determination of whether or not a liner is needed for stabilisation of SF/HLW emplacement tunnels in Opalinus Clay at repository depths (400 – 900 m) and its detailed properties (e.g. shotcrete or some other material) cannot be made until a URL is constructed at the disposal site (~ 2025). Nevertheless, with experiments at the Mont Terri rock laboratory, process understanding of geomechanical behaviour of tunnels in Opalinus Clay is being improved and work will continue for the next years. The implications of liners in terms of the safety concept and process understanding are being considered in laboratory, URL and modelling studies. The technical issues and associated safety concept issues are discussed in Section 6.5.3.3.3.

Technology for monitoring

Great experience in the area of monitoring methods and instruments will be available by 2035, because various repositories with corresponding monitoring programmes will have been in operation for many years worldwide by the time repositories in Switzerland will be licensed for operation. This includes repositories in Finland, Sweden, USA and France. Nevertheless, Nagra will participate in international projects to develop adequate monitoring concepts and equipment. Additional knowhow-development is expected through hands-on experience on monitoring of large-scale experiments in underground rock laboratories.

Technology for retrieval of wastes

Some countries have specific requirements for demonstrating the feasibility of waste retrieval (e.g. France, Switzerland) or are developing canister retrieval methods as part of the overall technology of repository implementation (e.g. Sweden). In Switzerland, the demonstration of retrievability of wastes is required for the licence for repository operation (L/ILW ~ 2030; HLW ~ 2045), thus considerable experience in this area should be available from other programmes. The degree to which this will prove to be valuable depends on the similarity in the engineering approaches.

Reprocessing and transmutation technology and associated technologies for waste solidification

Several countries (notably France and Japan) reprocess their spent fuel and are as well active in the area of research into transmutation technology. Regarding transmutation, methods are under study that could considerably reduce the overall toxicity of the waste, which is dominated by actinides. Major developments will be needed to achieve this and at present there is little discussion in transmutation studies of reducing the inventories of ^{129}I and ^{14}C, the nuclides that dominate radiological risks in long-term safety assessments. Irrespective of developments, it is widely acknowledged that geological repositories would still be required for HLW and for L/ILW, although with reduced waste inventories. Despite the significant research efforts in this field, there are considered to be very limited prospects for significant impacts on waste management programmes for the next several decades. A summary of the present status of partitioning and transmutation in relation to the implications for waste disposal is given e.g. in SKB (2007b).These areas will be monitored to evaluate possible implications for Nagra's future programme.

Within the scope of present-day reprocessing programmes, there is some ongoing study of advanced waste forms for certain long-lived radionuclides that are particularly significant in repository safety assessments. In particular, studies in Japan are focusing on methods for solidification of ^{129}I and ^{14}C that would provide very long-term isolation.

Treatment of wastes

Experience with waste treatment (conditioning) and with characterisation will be monitored, including work done in conjunction with decommissioning of nuclear power plants. This may also include intercomparison studies of waste characteristics.

4.4 The role of international collaboration

Nagra has many bilateral and multilateral agreements with other waste management organisations and research institutes. These provide invaluable opportunities for information exchange and offer important insights into technical and management issues in other programmes.

In addition, Switzerland has participated in multilateral RD&D projects in the context of the EU Framework Programmes for many years. These cover a broad range of areas and many ongoing projects are discussed in Chapter 6 in the context of the detailed research programme.

Nagra participates in various committees, working groups and projects of the OECD/NEA and is also involved in selected activities of the International Atomic Energy Agency (IAEA). This participation helps Nagra to maintain an overview on the developments at an international level and in other programmes and to participate in relevant joint projects. As noted earlier, Nagra also participates in international projects at Underground Rock Laboratories (URLs), including those at Mont Terri and at the Grimsel Test Site in Switzerland, but also participates in the Meuse-Haute Marne URL (ANDRA) and the Äspö Hard Rock Laboratory (SKB) studies and cooperates with the Japanese URL programmes. Furthermore, close contacts are maintained with the Belgian programme (HADES in Mol).

Work at Mont Terri has gone on for over ten years and at Grimsel for over 20 years. Both projects have a large number of participants including other waste management organisations, research institutes and regulatory bodies. An important point to note about both URL projects is that participation by any organisation in any given experiment is determined by the requirements and research needs of that organisation.

5 Strategic requirements and programme assumptions for RD&D for repository development

5.1 Introduction

As discussed in Chapter 3, there are five broad categories of requirements that provide guidance for repository development. These are:

- legal, regulatory and policy requirements
- shareholder (waste producers) needs
- technical programme (science and technology) requirements as assessed by Nagra
- authorities' recommendations
- expectations from scientific community and public

The consideration of strategic requirements arising from these sources provides the basis for the RD&D work programme to be performed over the next ~ 10 years as discussed in Chapter 6.

The strategic requirements that provide guidance for the repository concept and design are summarised in Chapter 5.2. These requirements principally arise from legal and regulatory documents, from the waste producers and from scientific and technological considerations. In Chapter 5.3, the strategic requirements for each programme stage are established and the main implications for future RD&D are outlined.

Note that the requirements arising from the recommendations of the authorities have been documented and analysed for the project demonstrating disposal feasibility for SF/HLW/ILW in Opalinus Clay in a separate report (Nagra 2008b); for the Wellenberg project this has also been done. These analyses are not further discussed in the remainder of this report.

5.2 Strategic requirements for repository concept and design

5.2.1 Radioactive waste and disposal concept

- All radioactive wastes arising from nuclear power production and from medicine, industry and research in Switzerland must be safely handled and disposed of by the waste producers. To keep track of the types and quantities of wastes and their relevant properties, a Model Waste Inventory (MIRAM) has been developed and is periodically updated (most recent version, see Nagra 2008f). This model inventory is periodically updated and contains information on both already existing wastes and wastes that will arise in the future. The maintenance of this inventory includes, as an ongoing RD&D activity, the characterisation of wastes and materials.

  Furthermore, with an adequate waste acceptance procedure the wastes arising are treated in a manner that ensures that the resulting waste packages can be disposed of in one of the Swiss repositories. For this purpose, preliminary waste acceptance criteria are developed.

- Deep geologic disposal of all radioactive wastes is prescribed by law for all radioactive wastes arising in Switzerland. The disposal concept includes two types of repositories, one for low and intermediate-level waste (repository for L/ILW) and one for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (repository for HLW). The two repositories can be located at two different sites or at one site (combined repository). Relevant RD&D activities include the stepwise refinement of the allocation of the wastes to the two repositories in the different stages of licensing and the development of corresponding waste acceptance criteria and procedures.

- The disposal schedule takes into account legal and regulatory requirements as well as additional conceptual requirements and programme assumptions. Based on current estimates, the granting of the general licence is foreseen in ~ 2018. The application for a nuclear construction licence for the L/ILW repository is planned in ~ 2025 and for the HLW repository in ~ 2035. The disposal schedule must be compatible with the waste arisings and with the interim storage capacity. It includes sufficient flexibility for the required RD&D.

5.2.2 Repository concept

- The repository concepts take into account the legal requirement that long-term safety is to be ensured by multiple passive safety barriers. As basic safety and design principles, balanced contributions of geological and engineered barriers to radionuclide retention and essentially complete initial containment within canisters for SF and HLW are required. The repository concepts include: i) the main facility, where the majority of all wastes will be disposed of and which will be backfilled and sealed in due time after waste emplacement; ii) the test zones, where site-specific data for the safety-relevant properties of the host rock are acquired to confim the safety; iii) the pilot facility, where the behaviour of waste, backfill material and host rock is monitored until the end of the monitoring period and in which data is collected to confirm safety with a view to closure. Relevant RD&D activities include the refinement of repository concepts with passive safety barriers and multiple safety functions and the adaptation to local conditions.
- For repository siting, a stable and sufficiently simple large-scale geologic-tectonic situation is required. Furthermore, conflicts with use of natural resources must be addressed. Such conditions ensure long-term stability with respect to geologic-tectonic processes (neotectonic activity, uplift/erosion, volcanic activity), good explorability of spatial conditions as well as a small likelihood of occurrence of human intrusion as a result of resource conflicts. Relevant RD&D activities are to screen the geological situations in Switzerland with a view to geologic stability and simplicity and to complement the understanding of long-term geologic-tectonic processes in Switzerland as well as to assess the potential for conflicts with the use of natural resources.
- Host rocks and confining units with favourable properties are selected within stable large-scale geologic-tectonic situations, ensuring a significant contribution of the geological barrier to the safety functions. Relevant RD&D activities include: The screening of rock types in Switzerland with a view to favourable rock properties and suitable spatial conditions, the selection of preferred host rocks and confining units, and the acquisition of data required for the demonstration of long-term safety, including a plan for exploration concepts both from the surface and from underground.
- The basic concepts for the engineered barrier system have already been developed (see Figs. 2-6, 2-7 and 2-8) and are expected to be retained. The concepts ensure a significant contribution of the engineered barrier system to the safety functions and the compatibility of the engineered barriers with the geological barriers of the preferred host rocks in the selected geologic-tectonic situations. Relevant RD&D activities are to refine the concepts for the engineered barrier system with a view to contributing to passive safety through initial containment and retention of radionuclides; to provide suitable boundary conditions for reliable emplacement of wastes and that allow retrieval of the wastes without excessive

demands; to develop concepts and stepwise refined designs (including design variants) of individual elements of barrier system; and to improve the understanding of long-term performance of the engineered barriers in the geological environment provided by the preferred host rocks.

- The repository concepts comply with the legal requirements of monitoring and retrievability of the wastes. The pilot facility serves to monitor the behaviour of waste, backfill material and host rock until the end of the observation phase and to collect data to confirm safety with a view to closure. As part of RD&D, a concept for monitoring and technologies for retrieval will be developed.

5.2.3 Feasibility of construction, operation and closure

- Concepts based on state-of-the-art technology already exist for the construction, operation and closure of geological repositories (infrastructure and technology for constructing the repositories, for handling the wastes, for emplacing the engineered barriers and for closing the facility). In general technological fields (robotics, control, etc.), considerable advances are expected up to the time when construction begins and these should be integrated into the final configuration of disposal technology. Sufficient flexibility should, therefore, be maintained to allow new technological developments to be taken into account. Also, in view of possible new nuclear power plants leading to an extended period of repository operation and monitoring, a concept for maintenance of important installations and replacement of components (e.g. waste receiving and handling facilities, monitoring instrumentation, etc.) will be developed.
- Concepts and designs of surface installations of the repository (waste receiving and handling facilities, shaft head-frame, ramp access) need to be developed, along with flexible approaches to arranging them. This will ensure minimisation of potential conflicts of spatial use and environmental impact during exploration, construction, operation, monitoring and closure.

5.3 Strategic requirements for programme stages

5.3.1 Overview of programme stages

The procedural requirements in the Nuclear Energy Act (KEG 2003) and Ordinance (KEV 2004) and the conceptual part of the Sectoral Plan (FOE 2008) and the Environmental Protection Act (USG 1983) that apply to the implementation of geological repositories are summarised in Nagra (2008a; Tables A.1-2 and A.1-3). The roadmap for implementation that has been derived based on these requirements and the implications for RD&D in the various stages are described in the following chapters.

Site selection in accordance with the conceptual part of the Sectoral Plan is carried out in three stages (see Section 5.3.2). Once the site and the conceptual design of the repository have been defined in the general licence, further nuclear licences according to the Nuclear Energy Act and Ordinance follow: the construction licence, the operating licence and – once the operational and monitoring phases are complete – an order for repository closure from the Federal Council. The most important features of the individual nuclear licences are listed below:

- **General licence**: The general licence defines the site and the main features of the project, including the approximate size and location of the main installations, the categories of waste for emplacement and the maximum disposal capacity. The general licence also specifies the suitability criteria to be observed in further repository implementation, as well as concepts for monitoring and for closure of the repository. The preliminary protection zone is also defined.

- **Nuclear construction licence**[11]: The construction licence defines the capacity of the repository and the key elements for technical realisation. It also includes a project for the monitoring phase and a plan for closure. It is the nuclear construction licence that defines the detailed lay-out of the facility.
- **Nuclear operating licence**: The operating licence defines the following: the capacity of the repository, measures for monitoring the environment and stages for starting up operation, the start of which requires a clearance from the authorities. It also defines the requirements applying to the wastes, in particular the activity limits.
- **Closure of the repository**: The Federal Council orders the closure work after the monitoring phase is complete, provided the long-term protection of man and the environment can be assured. After closure, the Federal Council can order a further limited period of monitoring.

5.3.2 Site selection and general licence

Because site selection and the general licence application are the key issues to be dealt with in the next ~ 10 years, these are discussed in more detail below.

The conceptual part of the Sectoral Plan for Geological Repositories was approved by the Swiss Federal Government on 2 April 2008. It clearly defines the role of the different stakeholders as well as the decision-making process and the input needed for the decision making for the selection of the sites for the two repositories (FOE 2008). The three main stages of site selection are according to the Sectoral Plan defined as:

- Stage 1: Selection and approval of siting regions
- Stage 2: Selection and approval of at least two sites for each of the repositories (one for high-level, long-lived intermediate-level waste and one for low-level waste)
- Stage 3: Selection of a site for each geologic repository and preparation of the application for the general licence.

The broad requirements on Nagra's project work for the Sectoral Plan are summarised in Table 5-1 and are discussed below.

[11] During construction and operation of the repositories, there will be a regulatory clearance procedure in addition to the nuclear licences.

Tab. 5-1: Nagra's responsibilities for each stage of the Sectoral Plan.

Stage / Main Focus	**Nagra's responsibilities**
Stage 1: Selection of geologically suitable regions for L/ILW and HLW	Propose siting regions both for the L/ILW and HLW repository based on existing information Inform, as requested, and respond to questions Contribute to the development of the evaluation methodology with respect to the spatial planning Provide information on land-use planning for the siting regions proposed
Stage 2: Selection of at least 2 sites for L/ILW and HLW repositories	Develop site-specific layout for the surface repository infrastructure for at least one site within each region in collaboration with the respective cantons and regions (participatory process) Perform provisional safety analyses Define the activities and initiate preparatory work for the environmental impact assessment Obtain the basic input for the evaluation of spatial planning aspects; contribute to the socio-economic studies, as requested Propose at least two sites for each of the repositories
Stage 3: Selection of one site for each repository	Perform additional geological investigations, as deemed necessary, in the selected sites Select one site each for the L/ILW and HLW repository for preparing the general licence application Reach agreement with Canton and Region on compensation
General licence application	Document the grounds for the site selection Provide a safety report Provide an environmental impact assessment Provide a report on the agreement with the spatial planning Provide further documentation as requested

Stage 1: Selection of geologically suitable regions for L/ILW and HLW

On behalf of the waste producers, Nagra was required to prepare proposals for siting regions for the L/ILW and HLW repositories as input to Stage 1 of the Sectoral Plan. According to Appendix 1 of the Sectoral Plan, the evaluation of siting possibilities has to be performed in five steps (see below) and to consider 13 criteria related to safety and technical feasibility (see Tab. 5-2).

Tab. 5-2: Criteria for site evaluation with a view of safety and engineering feasibility.

Criteria group	Criteria
1. Properties of the host rock and of the formations contributing to the waste isolation	Spatial extent Hydraulic barrier effectiveness Geochemical conditions Release pathways
2. Long-term stability	Geologic / tectonic stability Erosion Repository-induced effects Resource conflicts
3. Reliability of geological database / statements	Ability to characterise the formations Explorability of the spatial conditions Predictability of the long-term changes
4. Engineering suitability	Geomechanical properties and conditions Underground access and management of inflowing water

The 13 criteria are represented by a set of indicators which have to be used both for the evaluation that leads to the proposal of the possible regions and for rating the proposed siting regions. Nagra has prepared a report with the proposed siting regions for each type of repository (Nagra 2008c) which also explains the details of the evaluation that has been conducted in five steps in accordance with the Sectoral Plan:

- In a *first step*, the waste inventory, which includes reserves for future developments, is allocated to the L/ILW and HLW repositories. For the allocation of the wastes, the following properties have to be considered: inventory and radionuclide half-lives, selection of safety-relevant nuclides (evaluation of radiotoxicity), waste volumes, material properties (waste matrix, containers) and their possible impact on the host rock, heat production, content of potentially gas-producing materials (metals, organics) and content of complexants.
- Based on this waste allocation, the *second step* involves defining the barrier and safety concepts for the two repositories. With a view to evaluating the geological siting possibilities, quantitative and qualitative requirements for the different indicators on geology are derived on the basis of these concepts and the key properties of the wastes foreseen for disposal. These relate to the time period to be considered, the space requirements for the repository, the properties of the host rock (depth, thickness, lateral extent, hydraulic conductivity), long-term stability, reliability of geological findings and engineering suitability.

Steps 3 to 5 cover the evaluation of the geological siting possibilities:

- In the *third step*, the large-scale geological-tectonic situation is assessed and large-scale areas that remain under consideration are defined. From the viewpoint of long-term stability and explorability of spatial conditions, all large-scale geological-tectonic areas in Switzerland come into consideration for the L/ILW repository. For the HLW repository, the Alps, the Folded Jura, the western Tabular Jura and a small part of the Molasse Basin (western sub-Jurassic zone) are excluded.

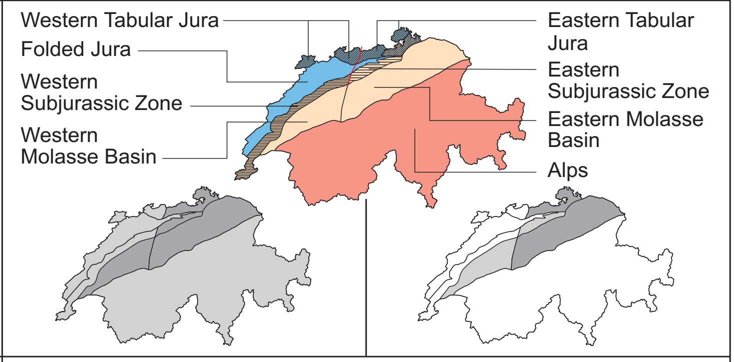
- The *fourth step* involves selecting the preferred host rock formations within the large-scale areas still under consideration. This is done in several sub-steps and leads to the following results: Proposed for the L/ILW repository are the Opalinus Clay with its confining units, the claystone sequence 'Brauner Dogger' with its confining units, the Effingen Beds and the marl formations of the Helveticum. For the HLW repository, the Opalinus Clay with its confining units is proposed as the preferred host formation.
- The configurations of the preferred host rocks within the large-scale areas under consideration are evaluated in the *fifth step*. Taking into account the presence of regional geological features (regional fault zones, over-deepened valleys resulting from glacial erosion, zones with indications of small-scale tectonic dissection, other zones to be avoided for reasons of neotectonics), preferred areas are identified within which the preferred host rocks can be found at a suitable depth and with sufficient thickness and lateral extent. The preferred areas are used as the basis for delimiting the geological siting regions. Some siting regions contain several preferred areas and sometimes more than one host rock type.

The stepwise procedure adopted for narrowing down the geological siting possibilities and identifying geological siting regions is documented in Nagra (2008c) and is summarised in Figure 5.1. More detailed information can be found in Nagra (2008d) and Nagra (2008e). Application of the procedure has led to the selection of 6 geological siting regions for the L/ILW repository (Südranden, Zürcher Weinland, Nördlich Lägeren, Bözberg, Jura-Südfuss, Wellenberg) and 3 geological siting regions for the HLW repository (Zürcher Weinland, Nördlich Lägeren, Bözberg). In three of the geological siting regions (Zürcher Weinland, Nördlich Lägeren and Bözberg), the possibility exists in principle of siting the L/ILW and HLW repositories together as a so-called "combined repository".

Steps according to Sectoral Plan	L/ILW Repository	HLW Repository
Steps 1 and 2: Waste allocation, barrier/safety concept and requirements	Definition of waste allocation and requirements concerning assessment time frames, space requirements, depth, host rock properties, uplift/erosion, etc., as well as rating scales	

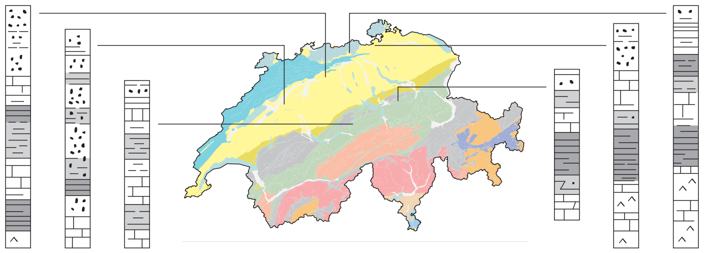
Step3: Identification and rating of the geological-tectonic areas to be further considered

Evaluation of the regional conditions in relation to uplift/erosion, geodynamics, geological complexity and spatial characteristics. The evaluation results in geological-tectonic areas rated as favourable to very favourable (dark grey), unfavourable to conditionally favourable (light grey) or unsuitable (white).



Step 4: Selection of preferred host rock formations

Selection of potential host rocks from the inventory of rock types (using 27 representative stratigraphic profiles). The rating of potential host rocks leads stepwise to the selection of preferred host rock formations within corresponding areas.



Step 5: Selection of the geological siting regions

Initially, within the areas to be considered further, host rock occurrences are identified with suitable depth and sufficient thickness. Then the proposed areas are delimited: the factors considered include regional fault zones, over-deepened valleys due to glacial erosion, zones with indications of small-scale tectonic disturbance and zones to be avoided because of an unfavourable tectonic regime (neotectonics). The rating of these areas leads to priority areas, which, together with other overlapping or nearby priority areas, result in the siting regions. The definition of the boundaries of the geological siting regions takes into consideration the uncertainties in the spatial information. The rating of the areas forms the basis for the rating of the geological siting regions.

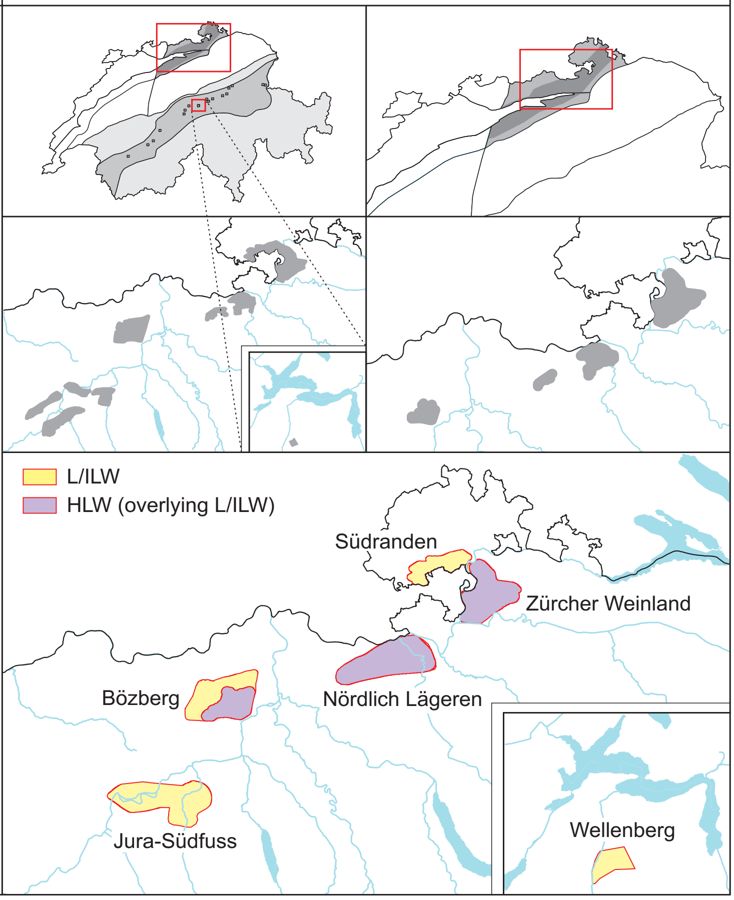


Fig. 5-1: The stepwise procedure adopted for narrowing down the geological siting possibilities and identifying geological siting regions for Stage 1 of the Sectoral Plan (Nagra 2008c).

The siting proposals will be evaluated by the federal authorities and, following a public hearing phase, the decision of the Federal Council on the geological siting regions is expected about 2½ years after the start of the Sectoral Plan.

In the course of Stage 1 of the Sectoral plan, Nagra also has to provide information on land use planning for the proposed siting regions. This information will be used by the authorities for their evaluations to define the region where the surface facilities will be placed and to define the communities for each siting region to be actively involved in the collaboration in Stage 2 and 3 of the Sectoral Plan.

Stage 2: Selection of at least two sites for L/ILW and HLW repositories

In Stage 2, at least two sites each for L/ILW and HLW repositories have to be proposed by Nagra. In a first step, within each siting region different possibilities for the location of the surface facilities will be investigated. For that purpose, an evaluation of land use and socio-economic impacts is carried out in collaboration with the Cantons concerned and regional consultation bodies. At this stage, the regional consultation bodies are given the opportunity to formulate sustainable regional development strategies, or to further develop existing ones. Nagra will also carry out provisional safety analyses for the different siting regions in order to check whether all siting regions are comparable with respect to long-term safety. The Sectoral Plan defines the methodology to be used for comparing the sites from the long-term safety point of view.

Based on the outcome of the provisional safety analyses and the evaluation of land use and socio-economic impacts, Nagra proposes at least two potential sites each for L/ILW and HLW. Co-location of both repositories at one site may also be considered.

The sites are then examined by the federal authorities and, if approved, are adopted in the form of intermediate proposals following a three-month consultation period (in accordance with the Swiss Federal Spatial Planning Act), with subsequent approval by the Federal Council.

Stage 3: Selection of one site for each repository and preparing the general licence application

In Stage 3, the sites approved at the end of Stage 2 are subjected to a more detailed examination and, where necessary, supplementary geological investigations from the surface (seismics and boreholes) will be performed. This will aid in providing the basis for Nagra to select for each of the repositories the site for which the general licence application will be prepared.

For the sites selected, in collaboration with the regional consultation bodies, the project for the repository is then defined in greater detail and the socio-economic aspects are subjected to closer scrutiny. The work and the activities in Stage 3 also provide the basis for the first stage of the environmental impact assessment.

General licence application

The general licence application has to cover a broad range of issues (Tab. 5-3). Because some of the information to be submitted is not directly dependent upon site-specific information, work on these issues will be started well before start of Stage 3 of the Sectoral Plan. It is also possible, to continue the RD&D activities on a number of issues before the sites have been selected in Stage 3.

Tab. 5-3: Information to be provided in the general licence application for each of the repositories.

Geological properties of site (geological synthesis)
Repository design concept
Concepts for monitoring and closure (including long-term archive and markers)
Waste categories to be disposed of
Safety for the operational phase
Safety for the post-closure phase
Environmental impact assessment
Compatibility with land-use planning
Comparison with other siting options with respect to long-term safety
Evaluation of the features of the site relevant for its selection
Cost estimate

After Nagra's submission of the general licence application, the responsible federal authorities will evaluate Nagra's general licence application. The general licence specifies criteria which, if not fully met, lead to the exclusion of a planned disposal zone due to lack of suitability. Stage 3 is completed after the site has been specified in the sectoral plan and the Federal Council has granted the general licence. Subsequent steps involve the approval of the general licence by the Parliament, which is subject to an optional national referendum.

5.3.3 Programme stages after granting of the general licence

After the granting of the general licence by the federal authorities, the following programme stages are envisaged:

- Construction and operation of a rock laboratory at the chosen site
- Construction of repository
- Operation of repository until final closure

The objectives of the work and key activities associated with these later stages are described at a very high level in Table 5-4.

Tab. 5-4: Key activities in the different programme stages after granting of the general licence.

Phase	Objective	Brief description of key activities
Rock laboratory	Licence for rock laboratory	Licensing procedure for field investigations (supplemented by investigations from the surface, rock laboratory)
	Construction of rock laboratory	Supplemented by investigations from the surface, rock laboratory construction (access tunnel, tunnels, galleries), construction-parallel characterisation, underground investigation
	Operation of rock laboratory	Initiation of experiments, performing experiments and monitoring, synthesis of results, preparing documentation for nuclear construction licence
Repository construction	Nuclear construction licence	Detailed design of surface and underground facilities; preparing documentation for review by authorities; decision by DETEC
	Repository construction	Construction of surface and underground facilities, preparing documentation for nuclear operating licence
	Nuclear operating licence	Review of documentation by authorities, decision by DETEC
Operation of repository until closure	Repository operation	Emplacing wastes in the pilot facility and measurements, packaging/emplacement of waste, continuous backfilling of SF/HLW tunnels, backfilling of full L/ILW & ILW chambers, sealing of full chambers, constructing new tunnels for SF/HLW, periodic safety assessment and reporting
	Closure of main facility/ (partial) dismantling of reception facility	Backfilling construction/operation tunnels, installing sealing structures
	Monitoring phase	Continuing measurements in pilot facility, other monitoring activities, periodic reporting
	Closure and decommissioning of entire repository	Backfilling tunnels, installing sealing structures, dismantling of surface facilities. Preparing documentation for closure licence
	Monitoring after closure of entire facility	Continued monitoring at the surface

5.3.4 Implications for RD&D

5.3.4.1 Main implications and programme assumptions for RD&D

Based on the previously discussed requirements and the status of work as indicated by the Nagra Sectoral plan Stage 1 submissions, the main implications and assumptions for future RD&D for the various fields of investigation are outlined below in Sections 5.3.4.2 to 5.3.4.6. The discussion provides the main focus of work for the subsequent Stages of the Sectoral plan and preparation of the general licence application and for later stages of repository development from the time of granting of the general licence through to repository operation. Prior to this discussion, the most important strategic assumptions regarding the approach for RD&D work to be done up to the time of the general licence application are briefly summarised:

- The scientific basis developed over the past approximately 30 years provides sufficient information to support the decisions to be made in Stages 1 and 2 of the Sectoral Plan, notably the identification of preferred host rocks and siting regions, the siting of the surface infrastructure of the repositories in the different siting regions and the development of the provisional safety analyses. For this purpose, the conceptual design of the repositories will be further refined.
- Within the process of the Sectoral Plan, the siting of the surface facilities will be fixed for the respective repositories.
- With the general licence, the site for the respective repository is fixed. This requires that a comprehensive synthesis of RD&D findings in all areas be made which is related to long-term safety and technical feasibility of construction, operation and closure of the repository. However, for the general licence the layout of the facility has only to be at the conceptual level and wherever appropriate, alternative concepts will be maintained for different elements of the repository.
- The detailed allocation of emplacement rooms and their detailed design as well as the detailed layout of system of engineered barriers will take place only after exploration from the underground (including results from the in-situ rock laboratory). Thus, this will be done in conjunction with the nuclear construction licence.
- In relation to the safety strategy for both the HLW and the L/ILW repository requires a substantial contribution of the host rock to radionuclide retention. Therefore, high quality host rocks have been proposed by Nagra for stage 1 of the Sectoral Plan. Thus, in the RD&D plan further work will be performed to improve the understanding of radionuclide retention in these host rocks and to further evaluate the potential effect of perturbing processes (e.g. excavation damage, gas generation, pH-plume, temperature for the HLW repository, etc.) on host rock performance. This includes studies of coupled processes (THMC (thermo-hydraulic-mechanical-chemical) see Section 6.5.4.2.4) for the whole system, which should also provide input to potential modifications of the system to keep perturbations at an acceptable level.

Because the present understanding of many topics discussed in Chapter 6 is considered sufficient for supporting the decisions to be made regarding Stage 2 of the Sectoral Plan, notably the development of the provisional safety analyses, the next comprehensive synthesis of RD&D findings in all areas will be made only for the general licence application (~ 2015[12]). Furthermore, the RD&D programme of technical work discussed in Chapter 6 is based on the assumption of the sedimentary host rocks proposed by Nagra in Stage 1 being judged to be suitable for the next stages of the Sectoral Plan process.

[12] All times mentioned are those mentioned in the conceptual part of the Sectoral Plan (FOE 2008).

5.3.4.2 Geological investigations

Site-related investigations

- According to the Sectoral Plan, a minimum of two sites each for L/ILW and HLW repositories must be proposed at the end of Stage 2. Site investigations from the surface in Stage 3 (beginning ~ 2013) must provide information sufficient for choosing the site for each repository type for preparation of the general licence application (~ 2015).
- Following the granting of a general licence, foreseen in ~ 2018, work would begin on field investigations in preparation for construction of an underground laboratory at the site. Prior to the field and construction work baseline monitoring programmes would be put in place.
- The field and underground investigations, including results from the underground laboratory, would provide the basis for the application for a nuclear construction licence for the L/ILW repository in ~ 2025 and the HLW repository in ~ 2035.

Regional geological investigations

- These involve ongoing activities such as geodetic measurements, operation of a microseismic network and general geoscience studies that provide support to the geosynthesis reports to be prepared at various project stages (see below). This will take place for Sectoral Plan Stage 2, the general licence application (~ 2015) and the nuclear construction licence application (~ 2025 for L/ILW and ~ 2035 for HLW).

Improving geological process understanding

- Ongoing activities in this area include, e.g. solute and gas transport processes and geomechanical processes. Studies are continuing in these areas in the present underground laboratories and will be further pursued in the site underground laboratories, with results flowing into the various geosynthesis reports to be prepared at various project stages (see below).

Geological reports and geo-synthesis reports

- The results of all relevant geological investigations will be integrated into geological reports or geosynthesis reports required for the various decision points, i.e. to support the provisional safety analysis in Stage 2 of the Sectoral Plan, the general licence application (~ 2015), and the nuclear construction licence application (~ 2025 for L/ILW and ~ 2035 for HLW).

5.3.4.3 Safety assessment

Safety analysis methods

- The present safety assessment methodology is being further developed through international cooperation. The developments support the periodic preparation of long-term safety reports (see below).
- The development of minimal requirements for components of the disposal system is an ongoing activity that requires an evaluation at each important milestone, see e.g. requirements on geology for Stage 1 of the Sectoral Plan (Nagra 2008e). Also for the general licence application (~ 2015) an evaluation of requirements will be made.

Models and data for long-term safety analysis

- For each repository development stage, the scientific specialists in the various disciplines must update the state of knowledge and evaluate the adequacy of models that represent the processes in safety analysis. This includes evaluating the need for detailed models of processes to be abstracted or simplified for application in system safety assessment and the suitability of such adaptations. Where required, improvements are made to the models and the associated databases are updated. In particular, for the general licence application, codes are being developed for a more comprehensive probabilistic analysis.

Long-term safety analysis reports

- In the context of each repository development stage, a long-term safety assessment report is required. Such reports must be prepared for Stage 2 of the Sectoral Plan (provisional safety analysis), for the general licence application (~ 2015), and for the nuclear construction licence application (~ 2025 for L/ILW and ~ 2035 for HLW).

Operational safety analysis reports

- Reports on safety analysis of the operational phase of repositories are required for the various stages of repository development. Furthermore, internal studies on operational safety are being performed to provide feedback on the layout of the facilities and the operation scheme. These reports are expected to become increasingly detailed in moving from the general licence stage (~ 2015) to the construction (~ 2025 for L/ILW and ~ 2035 for HLW) and operation (~ 2030 for L/ILW and ~ 2050 for HLW) licence stages, as more detailed design information becomes available.

5.3.4.4 Information on radioactive waste

Waste inventory and logistics

- Data and information on the various radioactive wastes, including the conditioning methods, is continually updated in co-operation with the waste producers. This information will flow into the provisional safety analysis of Stage 2 of the Sectoral Plan and the general licence application (~ 2015) and will be updated as required for later licensing stages.

Properties of HLW and spent fuel

- Improvements in the understanding of processes associated with HLW and spent fuel will be incorporated into the safety assessment for the general licence (~ 2015) and for later licensing stages.

Waste conditioning

- Studies on possible improved conditioning methods are ongoing.

Gas production

- Information on gas production as a result of degradation of organics and corrosion processes is being further developed and will be incorporated into the provisional safety analyses for Stage 2 of the Sectoral Plan and for the general licence application (~ 2015) and for later licensing stages. The evaluation of alternative waste conditioning methods may also lead to revisions in inventories of such materials and in the associated estimates of gas production.

5.3.4.5 Repository concept and engineered barrier system

Concept for the repository layout and for the engineered barriers

- The basic concept for the engineered barriers for L/ILW and HLW is expected to be retained. The studies will examine various aspects in more detail, including alternative design concepts and materials and the information will be incorporated into the general licence application.
- The methods for using bentonite blocks and pellets for backfilling around HLW canisters will be further developed. A reference concept will be developed for the general licence application (~ 2015), although the possibilities to use alternative materials is expected to remain open until the nuclear construction licence application (~ 2035 for HLW).
- A reference concept for cement-based backfill for ILW and L/ILW caverns will be developed for the general licence application (~ 2015), although the possibilities to use alternative materials are expected to remain open until the nuclear construction licence application (~ 2025).
- Materials for SF and HLW canisters and design concepts will be further evaluated for the general licence application (~ 2015) and the choice of material and design concept will be left open at that time. A definitive decision on the canister concept and material will be made in the period leading up to the construction licence application (~ 2035).

Improving process understanding in the near-field

- The improvement of understanding of the behaviour of safety-relevant radionuclides in the near-field is an ongoing activity with the objective of supporting the safety analyses performed for the various decision points. The next major synthesis of this information will be performed in the context of the general licence application (~ 2015).
- Improvement of understanding of coupled phenomena (including repository induced effects such as excavation damage, gas, temperature, pH-plume) is a continuing focus of research in laboratory and underground research laboratory investigations. Studies at Mont Terri and

other underground laboratories will continue to be pursued and additional investigations will be done in the underground laboratory at the disposal site. The next major synthesis of this information will be performed in the context of the general licence application (~ 2015).

Monitoring and retrievability

- A report on the monitoring concept for the L/ILW and HLW repositories will be developed for the general licence application (~ 2015). The associated studies, including work on instruments and techniques, will be progressively deepened and the approach developed in more detail for the construction licence application (~ 2025 for L/ILW and ~ 2035 for HLW). Technology for retrievability will be developed and a demonstration of retrievability will be performed in the period prior to the repository operation licence (~ 2030 for L/ILW and ~ 2040 for HLW).

Repository facilities and operation concepts

- Work is in progress to develop the concept for the various modules of the repository surface facilities (access, waste receiving and handling facilities, shaft head-frame, ramp access), and underground facilities (construction and operations tunnels, pilot facility, waste emplacement tunnels, underground test facility). The design concept also involves consideration of operational aspects. The modules for the surface facilities and the options for layout of underground facilities provide the basis for the site-specific allocation of surface infrastructure to be performed in Stage 2 of the Sectoral Plan.
- For the general licence application (~ 2015) the facilities layout concept will be adapted to the proposed repository sites for L/ILW and HLW and take into account the results of the field investigations in Stage 3 of the Sectoral Plan.
- Following the application for the general licence, the design studies will be further developed. The work will support preparation of documents for the authorities' review of an application for construction of an underground laboratory at the site. The detailed layout of the other facilities at the site will be developed for the nuclear construction licence application (~ 2025 for L/ILW and ~ 2035 for HLW) and will also take into account the results from underground exploration and from experiments in the underground laboratory.
- For the construction and operation licence, other aspects also need to be considered, these include security and for the HLW repository, the issue of safeguards.

6 Overview of the technical programme of work

6.1 Structure of the work programme

The work programme is described using a similar structure as for the Waste Management Programme (see Nagra 2008a, Appendix A-3.2). Note that studies both for the SF/HLW/ILW and the L/ILW repository are included and are discussed together under the same thematic headings. The scope and amount of work done specifically for the L/ILW programme to improve process understanding and development of methodology are quite limited, for the following reasons (depending on the specific programme area under consideration):

- there is a high degree of overlap and synergy between areas of work required for the SF/HLW/ILW and L/ILW programmes (e.g. safety assessment methodology, geochemical retention, cementitious materials and high pH effects, and gas-related processes), thus in these areas the scientific basis within the SF/HLW/ILW programme provides much of the basis for the safety assessments required for the L/ILW repository
- the requirements on the performance of the different elements are less stringent and thus also the level of understanding for the different processes is less ambitious for the L/ILW repository
- for L/ILW disposal, there are no thermal issues in the list of RD&D items, because of the low thermal output of the wastes
- the disposal of L/ILW is considered a mature technology, as evidenced by licensing and operation of such repositories in other countries. As a result, the focus of work is more related to the overall assessment of suitable host rocks and some focused technical development issues

The current RD&D programme of work as described in the remainder of Chapter 6 is largely focused on providing the basis for the synthesis needed for the general licence applications for the repositories for SF/HLW and L/ILW around 2015. Nonetheless, there are a number of specific areas where information will be drawn together for Stage 2 of the Sectoral Plan for preparing the proposal of a minimum of two sites each for the SF/HLW/ILW and the L/ILW repositories. These areas are noted below in the various subject areas and include: i) development of modular facility concepts that are adapted to the potential SF/HLW/ILW and L/ILW repository sites in Stage 2 of the Sectoral Plan, and ii) provisional safety assessments for each potential repository site proposed in Stage 2 of the Sectoral Plan to check that all proposed sites are comparable with respect to long-term safety (as required by the Sectoral Plan). The documentation of the safety assessments also includes justification of the data used. For that purpose, geological reports will be prepared for each proposed siting region in which all relevant geological information and data are documented.

6.2 Geological information

The geological information needed can be divided into the following broad areas:

- properties and characteristic features of host rocks and confining units
- geometry of host rocks and confining units, including regional geological elements (regional faults, overdeepened valleys due to glacial erosion, etc.)
- state parameters for key safety-relevant parameters (e.g. hydraulic heads, stress)
- long-term geological evolution (e.g. crustal movements, regional and local erosion)

In the Sectoral Plan, the following approach is taken. The proposals of siting regions in Stage 1 of the Sectoral Plan were developed based on existing information. Furthermore, for stage 2 the data to be used will be based mainly on existing information, according to the following approach: the properties of host rocks and confining units will be derived from data from boreholes of Nagra (some complementary analyses on core material is planned) and boreholes from third parties (partially also through participation of Nagra in investigations of third parties), from observations in railway and road tunnels and for some of the host rocks from underground rock laboratories; the geometry of various geological units and elements will be based on reflection seismic surveys of Nagra and of third parties, borehole information and outcrop mapping (mainly existing geological maps); the state parameters will be derived from data from boreholes of Nagra or third parties or from conceptual considerations; and the assessment of long-term geological evolution will be based on Nagra's regional programme (monitoring of movements through geodetic surveys, monitoring of seismicity) and on more localised studies. For all areas, general progress is being monitored (e.g. research projects of third parties). In Stage 3 of the Sectoral Plan and for the general licence application, field work from the surface (reflection seismic surveys, boreholes) is planned[13]. After granting of the general licence, construction of a site-specific underground rock laboratory is planned and exploration of the site from underground (exploratory drifts) is foreseen.

6.2.1 Complementing the geological information base for the potential siting regions and sites for Stage 2 of the Sectoral Plan

Objectives of work – According to the Sectoral Plan, in Stage 2 a provisional safety analysis[14] must be made for all sites / siting regions. The information on the siting regions must be sufficient to allow such provisional safety analyses. Nagra is of the opinion that the available information basis is sufficient. However, this assessment needs to be substantiated[15] and will then be discussed with the Federal Nuclear Safety Inspectorate (ENSI). Nevertheless, all opportunities will be used to enhance the existing information base, including surface mapping and regional investigations, complementary analyses on existing core material, participation in investigations of third parties and use of information from third parties.

Status of work – Regional and more localised investigations have been carried out by Nagra in various past projects. In preparation for Project Gewähr and during later stages of the HLW programme significant effort was put into seismic investigations of Northeastern Switzerland. The 2D seismic lines, conducted between 1982 and 1992 (Sprecher & Müller 1986, Naef et al. 1995), were complemented by the data sets compiled by the oil and gas industry resulting in a nearly complete coverage of the eastern Swiss Molasse basin and the eastern Tabular Jura (Nagra 2008c). The analysis and interpretation of these data sets are the basis of the structural models of this area. The 3D seismic survey in the Zürcher Weinland gave excellent structural data for a potential siting region of about 50 km^2 (Birkhäuser et al. 2001).

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[13] For Stage 2 of the Sectoral Plan an evaluation needs to be made to check the appropriateness of the available geological data for the provisional safety assessments. If the available data are considered insufficient, field work must already be done for Stage 2.

[14] According to the Sectoral Plan, one of the main aims of the provisional safety analyses is to provide the information for a comparison between the different sites considered in Stage 2 to ensure that the sites proposed for further investigations at the end of Stage 2 have a similar level of long-term safety.

[15] The final evaluation has to take into account the methodology for the provisional safety analyses. This methodology was at the time of preparing this report still under development by ENSI. Furthermore, the evaluation has also to consider the (provisional) outcome of the authority review of the Nagra proposals for Stage 1 of the Sectoral Plan.

In addition to the investigations of the HLW programme, local 2D seismic investigations were carried out in the Wellenberg region (Nagra 1997).

The seismic data were calibrated by borehole measurements in deep boreholes drilled by Nagra or other organisations (oil / gas, geothermal or thermal / mineral water industries. Nagra's multi-purpose boreholes were used mainly to provide geological, hydrogeological, geochemical, physical and rock mechanical parameters of host and surrounding rocks. The measurements in these boreholes and the investigations on core samples were concentrated on crystalline rocks, Opalinus Clay and Helvetic marls as potential host rocks for a repository. The data base on other rocks is rather limited but still provides useful information on other potential host rocks and surrounding aquifers. During recent years, boreholes drilled by third parties (e.g. geo-thermal wells) were used to obtain additional information (add-on projects) on potential host rocks (e.g. Effingen Beds, Molasse) or on studies addressing glacial erosion (research project borehole Wehntal).

Focus of work – The main aim of Stage 2 is to develop the necessary geological data sets for the provisional safety analyses and for the work related to the conceptual design studies for the repository layout. For that purpose, the existing data base will be complemented with additional information specific to the siting region e.g. through specific surface mapping and re-analysis of existing data (e.g. reprocessing of seismic data with a new methodology). Furthermore, any information on the host rocks from third parties (if needed, complemented by investigations on behalf of Nagra) and information from the on-going regional studies (see Section 6.2.3) will be used.

6.2.2 Site investigations for at least two sites each for the L/ILW and HLW repositories during Stage 3 of the Sectoral Plan

Objectives of work – According to the Sectoral Plan, a minimum of two sites each for the SF/HLW- and the L/ILW repositories must be proposed at the end of Stage 2. Site investigations from the surface in Stage 3 (beginning ~ 2013[16]) must provide information sufficient to select preferred sites for the general licence applications (~ 2015) for the two repositories. The site investigations from the surface are intended to provide updated and reliable data sets for the geometry of the sites and for the structural elements (fracture zones, faults, etc.). The investigations will also provide information to confirm and complement the existing data sets about the potential host rocks, confining units and surrounding rocks with special emphasis on hydro-geological, mineralogical, thermal and mechanical parameters as a basis for transport models, construction planning and process models. This includes parameter ranges to describe the lateral or vertical heterogeneities of the host rock to allow optimisation of the repository layout. The data sets are also used for investigation of relationships between different parameters to improve process understanding. Additional purpose-specific investigations may be necessary to evaluate questions with respect to erosion (e.g. impact of a deep valley caused by glacial erosion).

Information on the location and properties of fracture zones and faults at the sites investigated during Stage 3 are used for a more detailed layout of the repository.

State parameters (e.g. temperature, stress and pore pressure) are measured to provide more detailed boundary conditions for the necessary modelling of hydrogeology and geomechanics as well as for a more detailed assessment of gas transport.

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[16] All the times reported in Chapter 6 are based on the time plan provided in the Sectoral Plan (FOE 2008).

Status of work – For two of the siting regions under discussion (Zürcher Weinland, Wellenberg), detailed investigations have already been performed.

Focus of work – Site investigations from the surface will concentrate on geophysical methods (e.g. seismics), geological mapping and investigations in deep boreholes in the sites proposed at the end of Stage 2 of the Sectoral Plan and confirmed by the decision of the Federal government.

Seismic investigations will be carried out to improve the knowledge of the structure of the subsurface, especially to investigate depth and thickness of the host rock and structural elements in the investigation area. It is envisaged to use 3D technology, but depending on the region and the given site conditions (e.g. land use, topography, permitting situation), it may be necessary to use numerous 2D lines instead of a 3D survey. In such a case, a dense network of 2D lines would be used.

Outcrops in the proposed siting region will be mapped to support the interpretation of the seismic data and to improve the detailed understanding of the tectonic setting.

Additional deep boreholes will be necessary to calibrate the seismic investigations and to provide a comprehensive data base on the host rocks, the confining units and the surrounding rocks. Borehole investigations will include in-situ testing (e.g. hydraulic tests, stress measurements, petrophysical and structural logging) and laboratory tests on borehole cores (hydrogeological, mechanical, thermal, mineralogical and geochemical investigations). Water samples of relevant formations in the exploration boreholes will be taken as far as possible (e.g. high enough transmissivity of the formation); in low-permeability formations hydrochemical and isotopic analyses of porewater extracted from cores will be performed.

The number, location and direction (dip, azimuth) of boreholes depend on the host rock and the local situation. Therefore, exploration concepts are being developed for the potential siting regions. In addition, Nagra will continue to participate in or add-on to investigations of third parties (e.g. geothermal investigations) if relevant data can be expected.

State parameters will be evaluated with in-situ tests (stress, temperature and pore pressure measurements) in boreholes and will be complemented by long-term measurements with specially designed monitoring systems.

Deep and shallow boreholes will also be used for baseline monitoring (see Section 6.5.5).

6.2.3 Regional investigations in the areas of geology, tectonics, hydrogeology and long-term geological evolution

6.2.3.1 Regional geological conditions

Objectives of work – The progress in science will be monitored and any new data from third parties will be evaluated to keep Nagra's information base on regional geology in the regions of interest up-to-date. This includes stratigraphic/sedimentologic, tectonic/neotectonic, and hydrogeologic information.

Status of work – For Stage 1 of the Sectoral Plan, the information available in the regions of interest has been collected, analysed and documented (e.g. literature survey, GIS-based data compilation), see Nagra (2008d).

Focus of work – The collection of published information and data will focus on the regions of interest. If feasible and justified, Nagra will also participate in investigations of third parties. The information will be evaluated periodically and used in corresponding geological reports and geosyntheses.

6.2.3.2 Regional hydrogeology and hydrochemistry

Objectives of work – Available data and information on hydrogeology (hydraulic properties of hydrostratigraphic units, hydraulic head data, hydrochemical and isotopic composition of deep groundwaters) will be collected to confirm / improve the understanding of the regional flow patterns in the relevant deep regional aquifers in the region of interest (in particular Upper Muschelkalk and the coupled system Upper Malm – Molasse) and to assess potential cross-formational flow along regional faults. If appropriate, hydrodynamic models will be developed. For that purpose and also as a basis for safety assessment, effective properties of the different rocks will be derived and a traceable methodology for deriving representative parameters for the host rocks will be developed.

Status of work – Concerning the major regional deep aquifers, the recharge and discharge areas of regional importance as well as the general flow patterns in the region of interest are known (e.g. Nagra 1988, Thury et al. 1994, Nagra 2002a). These are based on observations in deep boreholes and additional geological and hydrogeological investigations and observations made by Nagra and third parties. Furthermore, hydrochemical and isotopic studies performed by Nagra and third parties have provided additional independent arguments to constrain the flow systems in the deep aquifers (e.g. Schmassmann et al. 1984, Nagra 1988, Pearson et al. 1991, Nagra 2002a). In general, these data confirm the formation of specific hydrochemical characteristics of deep groundwater ("Stockwerkbau"). The temporal evolution of the flow systems in the regional deep aquifers are an important boundary condition for the understanding of present day porewater in Opalinus Clay (e.g. Gimmi & Waber 2004, Gimmi et al. 2007).

On a regional scale, a first hydrodynamic model of the deep flow systems was constructed in the framework of Nagra's Kristallin programme ("Regionalmodell 1984", Kimmeier et al. 1985) which was refined in the framework of Sedimentstudie 1988 ("Regionalmodell 1987", Nagra 1988). The models OPA 88 and USM 88 focused on regions of interest in Northern Switzerland for the two host rocks under consideration (Nagra 1988; Voborny et al. 1993). In the late 90's, a large scale hydrodynamic model of Central and Northern Switzerland was completed (Bouzelboudjen et al. 1997) that also considers the information from earlier Nagra studies. The hydrodynamic model of the crystalline basement of northern Switzerland was refined in the course of the Kristallin-I project (Voborny et al. 1994). For the Zürcher Weinland area, a local hydrodynamic model was established in the framework of Entsorgungsnachweis 2002 (Nagra 2002a).

Spatial variability of flow and transport properties of groundwater flow systems is a multi-scale phenomenon, essentially ranging from the pore level to the regional scale. A systematic methodology was elaborated in the context of the Wellenberg programme (Nagra 1997) to address upscaling of flow in fractured rock (hydraulic fracture network models). For this purpose the fracture transmissivities, derived from hydrotest interpretation were converted into effective hydraulic conductivities on the block scale, appropriate for local and regional scale modelling of groundwater flow. The methodology has been tested successfully and is ready for use for other regional scale applications, where discrete fracture network models need to be converted in stochastic continuum models. In addition, advanced upscaling methods were developed for host rock formations that are characterised by spatial variability of the hydraulic properties, such as the Effingen Beds (shown in the report) and 'Brauner Dogger' (a similar approach is possible) (Roeser et al. 2008; Lanyon 2008).

Focus of work – The collection of published information and data will focus on the regions of interest. The main emphasis is on published data. However, where appropriate and feasible, Nagra will support additional hydrotests and taking of water samples and will also participate in third party investigations. The information available will be evaluated periodically and used in corresponding geosyntheses. An evaluation will be made regarding what types of hydrodynamic models (regions to be covered, level of detail included) may be used to deepen the understanding of regional groundwater flow in the relevant deep aquifers based on today's geologic – hydrogeologic knowledge, taking into account today's technical possibilities (codes and computers). Such models may be used to evaluate the possibility and extent of cross-formational flow, to test scenarios of different transmissivities of regional faults and to constrain the importance of the sandy lithologies in the Keuper for the drainage of the generally low permeable sequence below the Opalinus Clay ("Untere Rahmengesteine"). As in the past (e.g. INTERREG III[17] initiative), an information exchange with the Baden-Württemberg geological survey is planned for the characterisation of groundwater flow in the border area Germany Switzerland.

Methodologies for the derivation of effective flow and transport properties will be further developed with focus on the potential host rocks Effingen Beds and 'Brauner Dogger'. This includes not only the upscaling of hydraulic conductivities but also the impact of conductivity upscaling on the transport characteristics, such as travel times and hydrodynamic dispersion effects. New research projects on upscaling have been launched recently at ETH Zürich (Institut für Umweltingenieurwissenschaften).

6.2.3.3 Regional long-term geological evolution

Objectives of work – Progress in the science will be monitored and new data will be evaluated to keep Nagra's understanding on the large-scale long-term geological evolution up-to-date. This large-scale information together with more local information is also used to evaluate the long-term evolution of the siting regions of interest. The phenomena of main interest are horizontal and vertical movements, differential movements and erosion (regional, localised).

Status of work – The possible scenarios of long-term geological evolution are of interest since many years and several corresponding evaluations have been made (Diebold & Müller 1985, Klemenz 1993, Müller et al. 2002) and used in the different safety reports. To provide a better basis, specific measurements (precision levelling (Schlatter 2007, Zippelt & Dierks 2007), GPS measurements (Wiget et al. 2007), monitoring of microseismicity (Deichmann & Rinderknecht 2005) have been made and specific field data collected (geomorphology, dating of gravel terraces). For Stage 1 of the Sectoral Plan, an evaluation of the relevant information available for long-term geological evolution has been made, see chapter 2 and 3 of Nagra (2008d).

Focus of work – The acquisition and interpretation of microseismicity data will be continued. Periodic geodetic measuring campaigns (precision-levelling, GPS measurements) will be supported and analysed. It is planned to install additional permanent GPS and microseismicity stations. In order to better understand linear erosion processes and erosion rates, dating of quaternary terraces and valley fills using novel techniques is planned. Quaternary surfaces and other indicators will be screened for neotectonics movements using the Digital Terrain Model (LIDAR) and complementary methods. Furthermore, Nagra will carefully follow the on-going scientific work with respect to conceptual geodynamic models. It is planned to develop kinematic models of the evolution of the Jura Mountains and the neighbouring areas and to test these models using numerical geodynamic modelling. The understanding on long-term geological evolution will be evaluated periodically and used in the corresponding geosyntheses.

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[17] European Community initiative aiming at stimulating interregional cooperation in the EU between 2000 and 2006. It was financed under the European Regional Development Fund (ERDF).

6.2.4 Improving process understanding of key phenomena for the potential host rocks

The level of understanding of most key phenomena for the potential host rocks must be significantly higher for the HLW-repository than for the L/ILW repository because the requirements on host rock are different (see e.g. Nagra 2008c, e. For the HLW repository with the Opalinus Clay as proposed host rock, a broad spectrum of information is available and with the rock laboratory at Mont Terri, an excellent platform for in-situ research is available.

For the L/ILW repository with the less ambitious requirements, for two of the potential host rocks the information base is rather broad (Opalinus Clay through the investigations for the HLW programme and the Helvetic marls through the extensive investigations of Wellenberg; see synthesis in Nagra 1997). For the other two host rocks (Effingen Beds, 'Brauner Dogger') information from boreholes can be used to derive the necessary understanding for a L/ILW repository, also using information from analogues (information from Opalinus Clay for 'Brauner Dogger'; information from Helvetic marls for Effingen Beds).

In this section, the key properties of the host rocks are discussed. This also includes a discussion of the repository-induced phenomena. However, the approach for an overall evaluation of the effects of the different repository-induced phenomena with a system model (THMC-modelling) is discussed in Section 6.2.4.4.

6.2.4.1 Radionuclide transport processes in host rock

Objectives of work – To broaden the understanding of radionuclide migration in the different host rocks and to evaluate the relevant radionuclide transport parameters in the required safety assessment studies[18]. The main questions to answer are related to the factors that control the radionuclide transport rates through the host rock, such as advection (permeability), diffusion (diffusion coefficients), porewater chemistry, porosity and rock microstructure including anisotropy. An important element in the understanding is the synthesis of information over different space and time scales, i.e. results from laboratory studies on Opalinus Clay (Van Loon et al. 2003, Van Loon & Eikenberg 2005, Van Loon et al. 2005), associated field studies at the Mont Terri URL (Tevissen et al. 2004, Van Loon et al. 2004) and the regional natural tracer profiles (e.g. oxygen and hydrogen isotopes and chloride) in the host rocks (Gimmi et al. 2007). The overall objective is thus to derive effective transport properties for the different host rocks based on a traceable methodology and to compile and discuss the independent evidence available that supports such derived properties.

Status of work – Work performed by PSI, University of Berne and Nagra has provided a strong scientific basis for describing the retention characteristics of Opalinus Clay (Nagra 2002c, Gautschi et al. 2004, numerous PSI reports) and of argillaceous rocks (Bradbury et al. 2008) and compacted clay mineral systems in general (Glaus et al. 2007). In the area of understanding diffusion processes of weakly sorbing and non-sorbing tracers, there is good agreement between laboratory and field experiments (Wersin et al. 2008, Tevissen et al. 2004, Van Loon et al. 2004). For more strongly sorbing tracers, the corresponding field experiments have not yet been started (see below). Also, for the Helvetic marls, a good scientific basis was developed within the Wellenberg programme (Nagra 1997 as well as Stenhouse 1995, Bradbury & Baeyens 1997c). The work on the Opalinus Clay, the Helvetic marls, on clay minerals and on compacted clay systems in general provides a good overall scientific basis for argillaceous rocks and can thus also be applied to the clay stones 'Effingen Beds' and the 'Brauner Dogger'.

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[18] The work to improve the detailed understanding of sorption mechanisms and the development of sorption data bases is discussed in section 6.5.4.1.

In order to better understand the transport of radionuclides through potential host rocks over very long time frames, great emphasis has been put on the study of natural tracers and partly also their profiles (e.g. Gimmi et al. 2007). These studies provide important information with respect to the transport characteristics of the rock types in general over very long timescales (e.g. in the quasi-stagnant porewaters as observed in Opalinus Clay, 'Brauner Dogger', Effingen Beds and Helvetic marls) and on the long-term behaviour of nuclides (e.g. for Cl^- in relation to transport of ^{36}Cl and ^{129}I). Information on natural tracers is available for all of the potential host rocks considered (Opalinus Clay and 'Brauner Dogger' in the Zürcher Weinland; Opalinus Clay at Mont Terri; Effingen Beds in Küttigen and Oftringen; Helvetic marls at Wellenberg), with the most extensive data base for Opalinus Clay. A comprehensive study of natural tracer profiles in a number of clay rocks was carried out for the CLAYTRAC[19] Project (Mazurek et al. 2009). The results provide strong evidence for diffusion-dominated transport of tracers in various clay rocks.

Focus of work – In the near future laboratory measurements (e.g. sorption) also on the 'Brauner Dogger' and the Effingen Beds are planned. Work on Opalinus Clay will also be continued with the aim of improving the general understanding which can also be applied to the other potential host rocks. For Opalinus Clay the diffusion experiments at the Mont Terri URL, including the DI-A[20], DI-B[21] and DR[22] experiments have been set up to investigate the long-term in-situ diffusion behaviour of radionuclides in Opalinus Clay. These large-scale field experiments are supported by laboratory diffusion and sorption studies at PSI. In- and through-diffusion experiments are essential for providing and validating diffusion parameters. These parameters are also used for the accompanying modelling exercises through which process-oriented transport models are improved.

The composition of the in-situ porewater plays an important role in determining radionuclide retention (Baeyens & Bradbury 1994, Bradbury & Baeyens 1997b, Bradbury & Baeyens 1998). Several experiments are being performed at the Mont Terri URL to enhance understanding in this area, including the PC[23], PC-C[24] and GD[25] experiments. The general understanding developed here can also be applied to the other host rocks.

After previous studies on non-sorbing and weakly sorbing nuclides, the focus is increasingly on the diffusion/retention of strongly sorbing radionuclides and on the diffusion behaviour of redox-sensitive radionuclides (see also Section 6.5.4.1). The migration of strongly sorbing tracers is also being investigated in the laboratory at PSI. The technical challenges involved in investigating strongly sorbing nuclides in the field are significant, in particular because transport distances into the rock within the time frame of experiments (a few years) are likely to be smaller than the thickness of disturbed rock created during the installation of the experiments. Redox-sensitive radionuclides (e.g. ^{79}Se) are of special interest since they are sensitive to pore-water parameters such as pH or Eh and can respond by changing their oxidation state. First experiments are now being started to investigate the migration of redox-sensitive nuclides. Radionuclide retention on Opalinus Clay and the other potential host rocks is discussed further in Section 6.5.4.1 along with the related studies on retention on bentonite (and cement-based materials), because the sorption phenomena are basically the same.

[19] CLAYTRAC: Natural Tracer Profiles Across Argillaceous Formations (OECD / NEA Clay Club Project).

[20] DI-A: Long-term Diffusion (Mont Terri experiment).

[21] DI-B: Hydrogeochemistry and Transport Mechanisms (Mont Terri experiment).

[22] DR: Radionuclide Diffusion and Retention (Mont Terri experiment).

[23] PC: Porewater chemistry (Mont Terri experiment).

[24] PC-C: Gas porewater equilibrium (Mont Terri experiment).

[25] GD: Analysis of geochemical data (Mont Terri experiment).

Experimental batch studies on dispersed systems and model development work and sorption modelling at PSI, performed partly within the completed EU FUNMIG[26] project will be continued and extended in order to develop and refine the ion exchange / surface complexation model for Opalinus Clay and the other argillaceous host formations (see Section 6.5.4.1). The existing empirical porewater chemistry model will be refined by including surface complexation reactions, and if necessary, reactions with organic matter.

6.2.4.2 Gas transport processes in host rock

Objectives of work – To develop models that can evaluate the impact of gas transport and release processes on safety of repositories for L/ILW and HLW and provide the basis for managing gas-related phenomena in the context of repository design. In order to achieve this, the focus is on improving the overall understanding of gas transport processes, describing potential gas transport paths from the repository through the low permeability host rock[27] and evaluating relevant gas transport parameters. Various gases may be produced in both HLW and L/ILW repositories, principally as a result of the corrosion of metals and (microbial) degradation of organic matter[28]. The principal impacts of gas are expected to be increased pressures and thus stress changes in the surrounding host rock. The creation of a sustained gas pressure in the near-field may affect water flow in the host rock, ramp and shaft and thus have some effect on the transport of dissolved radionuclides. Potentially, therefore, gas may affect the behaviour of the host rock as a pillar of safety. Results of the studies will be applied in the context of the provisional safety analysis to be performed for various repository sites in Stage 2 of the Sectoral Plan and later for the general licence application for the proposed L/ILW and HLW repositories at the chosen sites. Eventually, it is planned to perform site-specific studies in the underground laboratories that will be built at the selected sites.

Status of work – Nagra has achieved significant improvements in understanding of gas transport in low-permeability rocks in recent years (Nagra 1997, Nagra 2004, Marschall et al. 2005, Croisé et al. 2006, Nagra 2008g), but the processes involved are complex and mechanistic understanding is not yet fully mature. The present information nonetheless provides a basis for evaluating gas pressure development in repositories for L/ILW and HLW and supports the proposal that Opalinus Clay will be a suitable rock for disposal of both L/ILW[29] and SF/HLW for the repository concepts that have been evaluated (Nagra 2008g, 2002c, 2004). The analyses performed within the Wellenberg programme (Nagra 1994a, Nagra 1997) also lead to the conclusion that the gas generated will not jeopardise safety of a repository in the Helvetic marls. For the other two potential host rocks (Effingen Beds, 'Brauner Dogger') no specific investigations on gas transport have yet been performed. Based on the available experience[30], due to the heterogeneity in these rocks (bedding, discontinuities), gas release is expected to occur at moderate gas overpressures. Work will continue to confirm this by complementary laboratory experiments on core material, as discussed below.

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26 FUNMIG: Fundamentals of radionuclide migration (EU project).

27 This may include the release of gas along the access tunnels/shafts.

28 Gas generation including the possibilities of its reduction are discussed in section 6.4.3.4.

29 In the event that the Opalinus Clay (or any of the other potential host rocks) would have too low a permeability to release the gas at acceptable overpressures, the possibility exists to use specifically designed backfill and sealing materials to allow the gas to be released along the access tunnel and shaft (see Nagra 2008e).

30 The clay-rich parts of the 'Brauner Dogger' are very similar to Opalinus Clay and the Effingen Beds are similar to the Helvetic marls (investigated in depth for the Wellenberg site).

Focus of work – Current and future research activities concentrate on improving understanding of coupled hydromechanical and hydrochemical processes associated with gas transport in intact and fractured host rock and also consider the excavation-damaged zone[31]. Work on gas transport in the host rock includes the following aspects: (i) evaluation and improvement of the existing understanding of gas transport mechanisms, (ii) broadening of the databases on gas transport in ultra-low permeability rock formations, (iii) in-depth understanding of hydro-chemical interactions which could affect the gas transport capacity of the host rock around the backfilled underground structures (see Section 6.5.3.3.5), (iv) investigation of scale effects due to small-scale variability of rock permeability. The gas-related investigations comprise large-scale in-situ experiments, laboratory test programmes, modelling studies and international co-operation (evaluation of experience with and information on natural and man-made gas reservoirs).

A series of long-term in-situ experiments are being performed at the Mont Terri URL. The HG-A[32] experiment will provide information on gas transport through the Opalinus Clay and along sealing sections (including the excavation-damaged zone). In-situ water and gas injection tests in boreholes are being conducted as part of the HG-C[33] experiment, aimed at investigating the changes in gas and water permeabilities at elevated injection pressures (pathway dilation and gas fracturing). Diffusive and advective transport of dissolved gas (hydrogen) in Opalinus Clay is being investigated as part of the HT[34] experiment. Desaturation and resaturation processes in the unsaturated zone of a microtunnel are being studied in the ongoing VE[35] experiment. As part of the EU 7th Framework Programme, the experiment proposal PEBS[36] has been prepared, aimed at investigating non-isothermal resaturation processes in the near-field of a HLW/SF disposal system (including the unsaturated zone of the host rock). The HG-D[37] experiment will also be initiated at Mont Terri, which deals with studying reactive transport of gas (CO_2) and associated modelling work. Finally, further gas injection tests are planned in large diameter boreholes in the context of the Mont Terri research programme.

Comprehensive laboratory studies of the solute and gas transport properties of Opalinus Clay have been initiated (Nagra's RD&D projects THM-LabPerm[38] and THM-EDZ[39], Mont Terri project HA[40], SHARC[41] consortium and further collaborations with oil and gas industry). The studies cover a number of areas, including scale-dependency of gas transport, microstructure of Opalinus Clay and bentonite and techniques for measuring gas permeability. Several laboratories with international reputations are involved in the material characterisation programme using a variety of techniques to measure relative permeabilities and capillary pressure functions

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31 Work on specifically designed backfill and sealing systems to allow the gas to escape along the access tunnels / shafts at moderate overpressures ('Engineered Gas Transport System', Nagra 2008g) will also continue (see section 6.5.4.2.3).

32 HG-A: Gas paths (Mont Terri experiment).

33 HG-C: Long-term gas migration (Mont Terri experiment).

34 HT: Hydrogen transfer (Mont Terri experiment).

35 VE: Ventilation (Mont Terri experiment).

36 PEBS: Long-term performance of engineered barrier systems (EU project proposal).

37 HG-D: Reactive gas transport in argillaceous formations (Mont Terri experiment).

38 THM-LabPerm: Laboratory programme on the investigation of gas transport and pathway dilation process in Opalinus Clay and in buffer materials (Nagra RD&D project).

39 THM-EDZ: Development of THM-modelling capabilities for simulating the EDZ evolution before and after repository closure (Nagra RD&D project).

40 HA: Hydrogeological analyses (Mont Terri experiment).

41 SHARC: Shale Research Centre.

in order to increase confidence in the quality of the gas-related data base. The institutes involved include Universitat Politècnica de Catalunya (UPC), Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen, British Geological Survey (BGS) Nottingham, EMPA Dübendorf, EPFL Lausanne, Australian Commonwealth Scientific and Research Organisation (CSIRO) Perth, and Chevron Richmond. Recently started laboratory investigations are dedicated to the impact of hydrochemical interactions on the gas transport capacity of the Opalinus Clay and the repository backfill, respectively. A comprehensive experimental programme with a multitude of column tests and a mock-up experiment will be conducted as part of the EU Project FORGE[42] (7^{th} Framework Programme).

Modelling projects have been established in cooperation with universities and other academic institutions (Lawrence Berkeley National Laboratories, ETH Zürich, EPFL Lausanne, UPC Barcelona). Model development comprises upscaling of gas transport processes, interpretation of data from gas-related experiments and the integrated system modelling as input for safety assessment and considers also the development of THMC coupled process models. This model development is pursued within specific Nagra internal projects (e.g. Gas-MOD[43]), through international platforms (e.g. the IConnect project[44] and Äspö THM Task Force[45]) and through EU projects (e.g. FORGE). In relation to the potential transport of volatile ^{14}C, modelling tools will be further developed.

Co-operation will continue with the clay repository programmes in France (ANDRA) and Belgium (ONDRAF/NIRAS) that have similar research interests. Collaborations with other industries having knowledge of gas behaviour in rock, such as the oil and gas industry, in relation to natural gas storage and CO_2 sequestration, provide complementary insights into the gas transport issue. This is being pursued through both formal arrangements (e.g. an agreement with Chevron) as well as participation in relevant international conferences. An external expert group has been established to give advice on the overall approach of Nagra's gas-related studies and to perform reviews of Nagra's associated databases, models and technical reports.

Although the majority of work is focussed on Opalinus Clay, the understanding developed will also be used for assessing gas transport in the other potential host rocks. The gas-related data base for the Helvetic marls is already quite mature, comprising analyses from a considerable number of packer tests in the investigation boreholes of the Wellenberg siting area. For the other two potential host rocks (Effingen Beds and 'Brauner Dogger') it is planned to conduct further investigations.

6.2.4.3 Geo-mechanical processes in the host rock

Objectives of work – The objective of the work is to deepen the understanding of processes that govern the mechanical behaviour of potential host rocks in the near- and far-field of underground excavations for the HLW and L/ILW repositories. This should provide a suitable basis for optimising the lay-out of the repository emplacement rooms and sealing sections of the access tunnels (including construction methods) to keep excavation-induced damage to the rock at a reasonably low level. For the emplacement rooms of the L/ILW repository, this is less critical because flow along the emplacement rooms will anyway occur due to the higher perme-

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[42] FORGE: Fate of repository gases (EU project).

[43] Gas-MOD: Development of geoscientific modelling capabilities related to combined water/gas transport processes (Nagra RD&D project).

[44] IConnect: Integrated CONtinuum and NEtwork approach to groundwater flow and Contaminant Transport.

[45] SKB THM Task Force on engineered barriers, associated with the Äspö Hard Rock Laboratory.

ability of the cementitious backfill. Furthermore, for the L/ILW emplacement rooms massive concrete liners are acceptable; these create no additional challenge because large amounts of cement will anyway be in the emplacement rooms that can interact with the surrounding rock. The planned massive liner permits control of the geomechanical processes (deformation, etc.). However, for the HLW emplacement tunnels and for the sealing sections of both repositories, adequate process understanding is important to allow adaptation and optimisation of excavation techniques and support measures to ensure the optimum use of construction material.

The results are also used as a basis for evaluating self-sealing processes in the host rock (Section 6.2.4.5), gas transport processes in the host rock (Section 6.2.4.2), temperature effects (for HLW repository) and for an evaluation of overall system evolution.

Status of work – The process understanding for geomechanical behaviour of the Opalinus Clay as summarised in Project Entsorgungsnachweis Nagra (2002a) allowed demonstration of the general feasibility of the chosen design for a HLW repository in the Opalinus Clay at 650 m depth. For greater depths a liner may be necessary for HLW emplacement tunnels (see Section 6.5.3.3.3). A suitable geomechanical data set is also available for the Helvetic Marls (Nagra 1997 Müller et al. 2008); for the Effingen Beds a few data are also available (Jahns 2008), whereas the current geomechanical evaluation of the 'Brauner Dogger' is based on analogue considerations. For the repository for L/ILW, the greater strength of the Helvetic marls and of the Effingen Beds suggest that construction problems will be minimal, whereas the situation in the 'Brauner Dogger' will be comparable to that in the Opalinus Clay. In the 'Brauner Dogger' the heterogeneity due to the variable lithology at the m and sub-m scale must be considered for the rock mechanical analyses.

Currently, the process-related questions in geo-mechanics are being addressed in the Mont Terri URL. Conditions at the Mont Terri URL are complicated due to the several phases of tectonic overprint (Vietor et al. 2006, Corkum & Martin 2007). In particular, the Jura folding resulted in a low symmetry situation with inclined and non-aligned orientations of the principle stresses and the bedding planes. The understanding developed at Mont Terri is expected to be valuable for adapting and optimising the HLW repository design to the higher (but symmetric) stress situation and the simpler lateral bedding orientation for a repository at greater depth (500 to 900 m).

Focus of work – For the general licence applications further work is planned in the following fields. (i) Optimisation of design and construction methods for critical repository elements (HLW emplacement tunnels and the sealing sections of all repository types) considering also the restricted use of critical materials. This involves improving the understanding of the evolution of rock-mechanical conditions during construction, operation and after backfilling/closure. (ii) improving the methodology to determine in-situ stress. The stress field and its changes due to repository construction and operation are essential information for geomechanical model calculations (needed for design of underground openings, and assessing the long-term evolution) and are also important for gas release calculations.

The geomechanical laboratory programme for Opalinus Clay aims to improve the testing procedures and the process understanding of geomechanical behaviour in the pre-failure state as well as in the post-failure regime. These laboratory programmes are performed within the framework of the Mont Terri Project, the EU TIMODAZ[46] project and also take advantage of THM projects.

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[46] TIMODAZ: Thermal Impact On the Damaged Zone in a repository in clay host rocks (EU project).

In-situ experiments at the Mont Terri URL ranging from the borehole to the gallery scale investigate geomechanical processes around underground excavations (Wileveau et al. 2007). In the TIMODAZ project the near-field deformation around a borehole is being studied in detail. In the MB[47] experiment in conjunction with the extension of the URL, the deformation processes around full-scale excavations and the impact of support on deformation processes are studied. The DS[48] experiment in the Mont Terri URL aims to improve the methodology of stress determination and the understanding of stress controls in layered sedimentary sequences.

Geomechanical modelling based on the above laboratory and in-situ experiments will be used to improve the numerical simulation capabilities that are required to explore the behaviour of various design alternatives in clay-rich host rocks.

Besides the extension of the ongoing work, new experiments that are in the early stages of development at the Mont Terri URL will provide additional insight into geomechanical processes. These include the full-scale emplacement experiment, the sealing experiment and a comprehensive rock characterisation programme (combination of borehole logging and laboratory testing).

The data base for the Effingen Beds and the 'Brauner Dogger' will be extended by further investigations. If the Effingen Beds and/or the 'Brauner Dogger' are among the host rocks to be investigated during stage 3 of the Sectoral Plan, additional work will be done on cores from the respective boreholes.

6.2.4.4 Resaturation and thermal effects on the host rock

Objectives of work – Studies are performed to increase the understanding of thermal effects on the host rock with the main emphasis on the disturbed zone around the repository. The studies will provide the input for an overall evaluation of the significance of these processes for long-term safety. The main emphasis is on the HLW repository; for the L/ILW repository temperature-related processes in the host rock are less important. The studies should provide a basis for describing saturation of near-field rock during excavation and the decades following waste emplacement, when resaturation and the greatest heat generation will occur. The information obtained will also be used for optimising the repository lay-out.

Status of work – The assessment of coupled THMC processes has received increased emphasis since Project Entsorgungsnachweis. A comprehensive synthesis report on two heater experiments and a ventilation test have been completed as part of the Mont Terri Research programme (Göbel et al. 2007, Wileveau & Rothfuchs 2007, Mayor et al. 2007b). The studies helped to define more clearly the zone of significant disturbance and to check conceptual understanding. The macropermeability results obtained were consistent with laboratory results obtained on borehole core samples. Furthermore, a review of the THMC processes in the disturbed zone around a SF/HLW disposal system was produced in the EU NF-PRO project (Aranyossy et al. 2008).

Focus of work – Current and future research activities concentrate on an improved understanding of coupled THM (HLW repository) and HM (principally L/ILW repository) processes in the host rock, especially in the disturbed zone around the underground structures of a repository. Work includes the following processes: desaturation of the rock during the operational phase of the repository due to tunnel ventilation and resaturation and mechanical

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[47] MB: Mine-by test (Mont Terri experiment).

[48] DS: Stress determination and monitoring (Mont Terri experiment).

evolution of the host rock after repository closure under isothermal conditions (L/ILW repository) and non-isothermal conditions (HLW repository). The work includes laboratory and in-situ experiments and model development with the main emphasis on thermally induced damage and thermal recompaction.

A laboratory programme on drillcore material from the Mont Terri URL was launched with emphasis on the determination of THM material laws for the Opalinus Clay (THM-EDZ, THM-LabPerm). An in-situ heater experiment has been started recently at the Mont Terri URL as part of the TIMODAZ Project. In addition, two new experiments at Mont Terri are planned in the near future, including a full-scale heater test in the Gallery 2008 and a 1:2 scale experiment in the VE tunnel, the latter being incorporated into the EU project proposal PEBS (Long-term performance of engineered barriers).

Model development concentrates on the following aspects: (i) improvement of THM material laws for Opalinus Clay, (ii) development of systematic process abstraction methods for performance assessment and (iii) insight models of the evolution of pore pressure and stress around the backfilled tunnels of a SF/HLW repository.

6.2.4.5 Self-sealing processes in the host rock

Objectives of work – Self-sealing studies are performed to increase mechanistic understanding of the self-sealing of discontinuities and to understand the timescale over which self-sealing occurs. The self-sealing capacity of the host rocks are being investigated for both reactivated natural faults and repository-induced fractures (e.g. excavation damaged zone (EDZ)). The information developed will provide an improved basis for quantifying self-sealing. For the HLW repository, self-sealing of the EDZ of the SF/HLW emplacement tunnels is important and, therefore, the main emphasis of the studies is on Opalinus Clay. For the other host rocks for the L/ILW repository, (partial) removal of the EDZ in the sealing zones is feasible due to their rock-mechanical properties and thus, self-sealing of the EDZ is less important.

Transmissive fractures or faults are not observed in the Opalinus Clay for an overburden of more than ~ 200 m. Distinct fracture transmissivities might, in principle, result from the reactivation of natural faults and their interaction with excavation-induced fractures around underground structures. As noted in Smith et al. (2004), preferential flow in the EDZ of HLW emplacement tunnels could make some contribution to radionuclide transport from the repository under the assumption of negligible self-sealing. The self-sealing mechanisms are similar for reactivated faults and excavation-induced fractures (creep, swelling, disintegration, mineral precipitation). For the L/ILW repository, self-sealing of the excavation-damaged zone around the emplacement caverns is of less importance, and for the EDZ around the sealing sections special measures can be taken if needed (e.g. (partial) removal of the EDZ). Work will continue to broaden the information base on independent evidence (e.g. observations in tunnels and boreholes) and to improve mechanistic understanding. For both the HLW and the L/ILW repositories, investigation of the EDZ in the site-specific URL is planned.

Status of work – There is a significant body of evidence for the different host rocks that shows that self-sealing occurs if the overburden is of sufficient thickness. Furthermore, specific experiments have been performed to improve understanding of self-sealing. As part of the EU 6th Framework Programme, substantial efforts have been pursued in the projects EB[49] (Mayor et

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[49] EB: Engineered barriers (Mont Terri experiment and EU project).

al. 2007a), SELFRAC[50] (Bernier et al. 2007) and NF-PRO[51] (Aranyossy et al. 2008) to broaden the knowledge base on self-sealing processes in argillaceous formations. A state-of-the art report on the self-sealing capacity of argillaceous formations is being compiled as part of a comprehensive NEA/OECD initiative (Bock, *in prep.*).

Focus of work – Current and future research activities concentrate on an improved understanding of coupled hydromechanical and hydrochemical processes associated with the self-sealing of discontinuities in Opalinus Clay. Work on self-sealing in the host rock includes the following aspects: (i) continuation of compilation of phenomenological evidence, (ii) extension of the experimental database, both on the laboratory scale and in-situ, and (iii) further development of conceptual models and quantitative models for the simulation of self-sealing processes.

Phenomenological studies on natural faults were initiated at the Mont Terri URL and the Mont Russelin tunnel (partly faulted Opalinus Clay), comprising detailed mineralogical, structural and geochemical analyses of the faults and comparisons made with the undisturbed rock. Collaboration with the oil and gas industry will be sought, particularly in relation to desk studies on hydro-fracturing, CO_2 sequestration and 'cap rock' investigations.

A laboratory programme on core material from the Mont Terri URL was launched with emphasis on stress-dependent transmissivity of artificial fractures (LabPerm project). In-situ experiments on self-sealing are being conducted at the Mont Terri URL, including HG-A, focusing on self-sealing along the EDZ of a sealed tunnel and HG-C, focusing on pressure-dependent transmissivity of a hydraulic fracture.

Modelling tools for simulating coupled hydro-mechanical processes in fracture networks were developed in the context of the IConnect project. The modelling framework was applied successfully for simulating the self-sealing of the EDZ around a backfilled tunnel section in Opalinus clay (Lanyon 2005). Future developments will concentrate on the simulation of two-phase flow processes in deformable fracture networks.

6.2.5 Geological reports for sites for Sectoral Plan Stage 2 and for the general licence application

Objectives of work – All the relevant geological information and data for the siting regions and sites considered has to be analysed and the corresponding understanding will be documented in geological reports. These geological reports will also contain a geological data set that provides the geological information needed for the safety analyses and for the design concepts of the repositories. According to the nature of the different milestones, the level of detail will differ for Stage 2 and for the general licence application – for Stage 2 geological reports of limited extent will be produced, whereas for the general licence applications full geo-syntheses will be made.

Status of work – Nagra has considerable experience with preparing geological reports and geological syntheses, most recently with the extensive geosyntheses for two of the host rocks proposed in Stage 1 of the Sectoral Plan, i.e. Helvetic marls (Nagra 1993, Nagra 1997) and Opalinus Clay (Nagra 2002a). In addition, for the other host rocks proposed in Stage 1 of the Sectoral Plan, an evaluation of their relevant properties has been performed and the information available has been collected, analysed and documented (Nagra 2008d).

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[50] SELFRAC: Fractures and self-healing within the excavation-disturbed zone in clays (Mont Terri experiment and EU project).

[51] NF-PRO: Understanding and physical and numerical modelling of the key processes in the near-field and their coupling for different host rocks and repository strategies (EU project).

Focus of work – For Stage 2 of the Sectoral Plan for each of the siting regions the relevant geological information will be compiled and analysed. This also involves the development of the geological data sets for the provisional safety analyses as required by the Sectoral Plan. Thus, besides reference values for key phenomena also the expected range of parameters needs to be specified and their choice to be justified. In Stage 1 it will be clarified with ENSI if the information already available for the different host rocks (from the numerous boreholes, observations in tunnels and for Opalinus Clay also from the rock laboratory Mont Terri) and the siting regions forms a sufficient basis for developing the input parameters for the provisional safety analyses; if not, additional field work may be needed.

For the sites selected at the end of Stage 2 of the Sectoral Plan, additional field data from the field investigations performed in Stage 3 will become available. These, together with the already existing broad information base will form the basis for the geo-syntheses for the HLW and L/ILW-repositories for the general licence applications.

6.3 Safety assessment and clarification of safety-relevant phenomena

Safety assessment is the process of quantitatively and qualitatively evaluating the safety of a specific disposal system, which is a requirement for all major steps in repository development. The process requires application of a methodology for gathering and processing the required information regarding the initial conditions and long-term evolution of the geological and engineered barrier systems. This information is then used to perform an evaluation of whether or not the disposal system as a whole meets the requirements for long-term safety, which involves assessing the compliance with the dose and risk criteria given in the regulatory guideline G03 (ENSI 2009). The results of long-term safety assessments are presented in safety assessment reports, which are required for Stage 2 of the Sectoral Plan[52] and to support the subsequent general licence applications. In addition, for the general licence applications, operational safety reports will be prepared for both the HLW and L/ILW repositories.

The safety strategy requires that the impacts of the perturbing processes on the safety functions (see Chapter 2.4) be shown to be acceptable, or in the event that they are considered problematic, that design measures be taken to reduce the impacts to an acceptable level. This strategy drives in particular the studies of coupled processes (e.g. thermal and gas pressure impacts on the hydro-mechanical state of the rock, see Sections 6.2.4.2, 6.2.4.3 and 6.2.4.4, and of the near-field, see Section 6.5.4.2.4).

6.3.1 Updating and improving the methodology for safety analysis

Objectives of work – The broad objective of work in this area is to further develop the safety assessment methodology so that it meets the needs of future safety assessments. In particular, the methods must be appropriate for the provisional safety analyses that are required for Stage 2 of the Sectoral Plan and for the more comprehensive safety assessment for the general licence application. Particular focal points of the methodology development work include scenario analysis, FEP (features, events and processes) management and probabilistic safety analysis methods and tools. The work also encompasses improvements in the codes as well as defining the requirements for the data needed for the codes. A special emphasis is on the further

[52] For Stage 1 of the Sectoral Plan, no safety assessment report in the strict sense was required, but rather a report that defines and explains (i) the allocation of the waste to the two repository types HLW and L/ILW, (ii) the barrier system for the two repository types, and (iii) the requirements on geology for the two repository types from the point of view of long-term safety and technical feasibility (Nagra 2008e). For Stage 2, so-called "provisional safety analyses" are required (see Sectoral Plan Appendix III for definition).

development of Nagra's probabilistic safety analysis (PSA) capabilities. There is, however, no sharp division between deterministic and probabilistic codes. In principle, all deterministic codes can be used in a probabilistic environment. However, the construction of a PSA environment as well as the definition of the necessary input data (probability density functions) requires special attention at an early stage.

Status of work – Nagra has developed a structured approach for carrying out safety assessments and for safety case development that is consistent with current international views in these areas. The methodology is based on experience acquired by Nagra in carrying out several safety assessment studies, most recently Project Entsorgungsnachweis (Nagra 2002c), interactions with other waste management organisations and with Swiss regulatory authorities, and insights from participating in the committees of international organisations, in particular the NEA (NEA 2008). The methodology is being further developed to support the safety assessment for Stage 2 of the Sectoral Plan and for the general licence applications.

In the area of computer codes for radionuclide transport, a series of codes have been used to represent transport in the near-field and geosphere and distribution of radionuclides in the biosphere, with outputs from one code providing inputs for the next (i.e. the codes are not fully coupled). Additional codes have been developed for special scenarios in the assessment. Both deterministic and probabilistic modelling studies have been performed, with probabilistic assessment calculations focused on the assessment of a few selected scenarios. The main new developments since Project Entsorgungsnachweis are: (i) Improvements in the codes used in Project Entsorgungsnachweis for the HLW repository (specifically implementation of the ability to deal with transient flow fields); (ii) new development of a code for modelling radionuclide release and transport for the L/ILW repository; (iii) new development of a prototype of an integrated probabilistic safety assessment (PSA) tool that can handle transient two-phase flow in the near-field and in the geosphere (see also "focus of work").

Focus of work – Provisional safety analyses are to be performed for Stage 2 of the Sectoral Plan, which will focus on performing safety analysis for the different sites considered. The models and codes to be applied are either further developments of those that were used in Project Entsorgungsnachweis (for the HLW repository) or new developments (for the L/ILW repository). In addition, more qualitative safety evaluation aspects such as reliability of data and explorability of the sites will be incorporated into the assessments.

In most areas of further work on safety assessment methods and tools, new developments will be applied in the safety assessment for the general licence application. Work with international groups will continue so as to maintain a state-of-the art capability in assessment strategy and methodology. Safety strategy aspects are discussed and further developed within the context of participation in the NEA Integration Group for the Safety Case (NEA 2006, 2008). The FEP methodology will be updated, with input from the international FEP database (NEA 2006), FEP management approaches in other projects (e.g. ANDRA 2005a, Smith et al. 2007, SKB 2006a) and Nagra's own development work.

Several aspects of safety assessment methodology development are being pursued. The procedures for defining assessment cases are being improved. The method for quantifying risk, a requirement associated with Protection Objective 2 (ENSI 2009) is also being further examined. Approaches for performing safety assessment related to chemotoxicity of waste are also being developed. This requires updating of waste inventories to ensure coverage of chemotoxic elements and compounds, as well as developing methods for consequence analysis.

For the general licence application, the issue of accidental human intrusion (e.g. a deep borehole) into the repository will be further evaluated, in particular the effectiveness of countermeasures such as repository markers and archiving of information. Plausible scenarios through which intrusion might occur will then be examined in relation to these countermeasures.

The regulatory guideline G03 (ENSI 2009) requires that the impact of geological processes that may lead to an exposure of the repository to influences from the surface be evaluated in terms of regional radiological consequences. The models and methods to evaluate these impacts will be further developed.

A particular area of emphasis in the next several years involves improvements in the methods and codes for probabilistic safety assessment (PSA) calculations. A project has been started that is intended to improve both the method of integrating expert judgement into PSA calculations and the codes used for PSA. The probabilistic studies also involve development of an integrated radionuclide release code (IRRC), which will be able to deal with transient two-phase flow conditions and which can also be used as a benchmark for more simplified safety assessment tools. The project is being developed in the context of the EU PAMINA[53] project, which deals with many aspects of safety assessment.

6.3.2 Requirements management

Objectives of work – The objectives of work in this area are both to further develop and improve the overall methodology for implementing a requirements management process for the repository development programme, as well as to continue using the process to document the specific requirements for various elements of the repository system. The process is used to systematically derive the specific design basis requirements for repository components and layout from the results of long-term safety assessment and associated studies. It also addresses the issues of timing, level of detail and level of confidence (*"what information has to be available at what stage of repository development at what level of detail and what is the level of confidence needed?"*). The requirements are documented in a requirements management tool. The results of the work are applied in the context of the repository design and safety analysis and in the development of the information needed for the upcoming stages of the sectoral plan and the general licence application and have also been used in developing this report.

Status of work – The requirements management process is presently being defined in terms of the structure, content and procedures. The high level requirements (legal, regulatory and policy, see Nagra 2008a) along with the repository development objectives and principles (Nagra 2002c) have been documented. The requirements on the geology have been developed in the context of Stage 1 of the Sectoral Plan (Nagra 2008e). For other components, preliminary requirements have been developed.

Focus of work – The development of repository component requirements will continue. It is important to recognise the iterative nature of the process of developing requirements; i.e. the existing requirements will be refined as repository concepts are further developed. The requirements management process will be documented and maintained in a suitable software tool, with formal approval and control procedures developed within the Nagra QM process.

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[53] PAMINA: Performance assessment methodology to guide the development of the safety case (EU project).

6.3.3 Incorporating new knowledge related to geological processes, immobilisation, retardation and transport of radionuclides and waste properties into safety analysis models and data bases

Objectives of work – The overall objective is to incorporate understanding from research studies of radionuclide retention and transport in the engineered barrier system and host rock, as well as waste form characteristics (in particular release rates of radionuclides from spent fuel (matrix dissolution / cladding corrosion, instant release fraction) and from vitrified HLW (glass dissolution) and gas production rates for L/ILW), into safety assessment models and codes. The work encompasses adaptation of the radionuclide release and transport codes used in safety assessment to better represent the processes (model abstraction) and updating the databases of some specific processes, in particular sorption of radionuclides onto host rock and engineered barrier materials and solubilities of radionuclides in the near-field (see Section 6.5.4.1). To ensure the correct integration of the scientific basis into performance assessment, the scientific specialists in various areas are directly involved in the development of the relevant codes and data bases.

Status of work – The codes used for safety assessment calculations are being updated in order to make improvements dealing with more appropriate representations of some of the release and transport processes. These improvements will increase both the realism and the flexibility of codes. An integrated release and transport code has recently been developed that is suitable for modelling L/ILW caverns and ILW tunnels (Holocher et al. 2008). In addition, the near-field code STMAN has been modified to allow explicit representation of an advective transport condition at the boundary between a diffusion-dominated near-field and the host rock instead of the previously used mixing tank boundary condition (Nagra 2008h). Also, a new version of the geosphere transport code PICNIC has been developed that allows modelling of time-dependent flow fields (Robinson & Suckling 2008).

The present databases on radionuclide retention, solubilities and release rates from waste forms have been updated since Project Entsorgungsnachweis and are considered suitable for the Sectoral Plan Stage 2 provisional safety assessment studies, except for the need to address radionuclide retention in alternative host rocks for L/ILW.

Focus of work – The main areas of ongoing and future development involve (i) the iterative application and refinement of existing codes in the context of the Sectoral Plan and the general licence application, with concurrent development of the required datasets (specifically geodatasets for all potential host rocks proposed within the framework of the Sectoral Plan – Stage 1, see Nagra 2008c); (ii) the development of the necessary data bases for geochemical retention and transport in the different host rocks; and (iii) the further development of Nagra's probabilistic safety assessment (PSA) capabilities, encompassing the methodology, the PSA environment and the derivation of the input data (see Section 6.3.1).

For the general licence application, there will be a comprehensive synthesis in all areas related to abstraction of safety assessment models for radionuclide release and retention processes, which will be summarised in the safety assessment reports for the general licence applications and in various supporting documents.

In relation to model input parameter databases for radionuclide transport, the database on retention of radionuclides in host rocks, which is most advanced for Opalinus Clay[54], will be supplemented by databases for the other potential host rocks.

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[54] The sorption data base for Helvetic marls developed for the Wellenberg project will be updated.

6.3.4 Development of the biosphere model for calculation of radiological consequences

Objectives of work – In contrast to the near-field or the host rock, the biosphere is not considered to be a part of the repository barrier system. Biosphere modelling, however, is required to convert radionuclide releases from the barrier system into a dose to be compared with safety criteria. To this end, the objective is to provide the models (concepts and codes), input parameter data, and the model results required for the provisional safety assessments for Sectoral Plan Stage 2 and for the general licence applications.

Status of work – For the Wellenberg project and for Project Entsorgungsnachweis, stylised reference biosphere scenarios were defined based on present-day conditions. In addition, alternative stylised biosphere scenarios that might be expected to prevail in central (Wellenberg) or northern (Entsorgungsnachweis) Switzerland were defined (different climate conditions and geomorphological conditions). These scenarios were implemented in numerical biosphere models (Nagra 1994a, Nagra 2002c and d, Nagra 2003).

For the Sectoral Plan Stage 1, a reference biosphere scenario (corresponding to the reference scenario in Nagra 2002c, d) was used to convert calculated radionuclide releases from the geosphere to radiation doses. A set of alternative scenarios was defined to characterise the variability of the dose due to different biosphere scenarios throughout Switzerland under different climate conditions (warm/dry, warm/humid) and alternative exfiltration situations. In addition, a number of generic biosphere parameters were revised to reflect recent research that yielded new knowledge on the behaviour of certain radionuclides in the biosphere (e.g. solid/liquid partitioning coefficients, transfer factors of radionuclides within the food chain) (Brennwald & Van Dorp 2008).

Focus of work – For the future safety assessments, the focus will be on ensuring that Nagra's biosphere modelling remains state-of-the-art, taking into account on-going developments. This includes determining the sensitivity of the various model parameters to allow focusing on the relevant parameters when developing new parameter sets, revising and updating the generic biosphere data, determining typical (stylised) biosphere parameter values for the regions/sites considered in future assessments, developing and improving model concepts and implementing them in the computer code used for biosphere modelling (e.g. uptake of ^{14}C by plants, behaviour of ^{79}Se in the soil / plant system), developing and improving models to illustrate and study the potential effects of a repository that is subject to influences from the surface due to erosion and participating actively in work with international organisations focusing on biosphere modelling for radiological safety assessments (BIOPROTA (Biosphere aspects of assessment of long-term impact of contaminant release associated with radioactive waste management), IAEA/EMRAS (Environmental Modelling for Radiation Safety), and ICRP (International Commission for Radiological Protection)).

Focusing on these aspects will allow Nagra to maintain and improve the scientific and technical basis for biosphere models that will be used in future safety assessments.

6.3.5 Long-term safety reports

Objectives of work – The objectives of this work are to provide the safety reports required for the Sectoral Plan and the general licence application for both the L/ILW and HLW repositories. Special attention is placed on developing an appropriate reporting structure for Stage 2 of the Sectoral Plan, where on the order of ten simultaneous provisional safety analyses for the different sites and repository types will have to be compiled and documented (see Section 6.3.1). Also for the general licence applications the structure of the documentation will be re-evaluated.

Status of work – Work on the reporting structure for Stage 2 of the Sectoral Plan has started. Regarding the general licence application, the developing state-of-the-art in compiling safety assessment reports is being closely monitored, e.g. by active participation in relevant international projects (EU project PAMINA, NEA Integration Group for the Safety Case) and by monitoring safety cases developed by other organisations.

Focus of work – The focus of the work is on the preparation of the reports for Stage 2 of the Sectoral Plan. Some of the analysis required is specific to the Swiss programme and has to be developed by Nagra together with suitable contractors. For the reports for the general licence application, the experience gained in compiling previous long-term safety reports (specifically for the L/ILW repository at the Wellenberg site and for a HLW repository in the Zürcher Weinland for Project Entsorgungsnachweis) and the corresponding review comments by the authorities will be used, together with insights gained in following the relevant international developments (see above).

6.3.6 Operational safety reports

Objectives of work – The objectives of this work are to develop the basis and the know-how needed to perform the operational safety assessments required for the general licence application for both the L/ILW and HLW repositories and to complete the associated operational safety reports. An important aspect of these safety studies is to provide feedback to repository design and operation from the point of view of operational safety.

Status of work – A complete operational safety assessment was carried out for the general licence application for Project Wellenberg (L/ILW repository). No general licence application and thus no full operational safety assessment has been prepared yet for the HLW repository. However, for specific HLW and ILW waste types, some work regarding operational safety was carried out in the context of assessing their acceptability. Also in Project Entsorgungsnachweis a broad qualitative analysis of operational safety was performed (Nagra 2002b).

Focus of work – The work will be carried out in close collaboration with contractors with established experience in operational safety assessments of facilities where radioactive material is handled. The scope of the work is presently being defined.

The general approach will be to first identify the standard operational procedures and conditions for the L/ILW and HLW repositories. Then, catalogues listing and describing possible deviations from these procedures and conditions will be established. Finally, the potential safety-relevant consequences of such incidents will be assessed. Both radiological and non-radiological consequences will be taken into account.

It should be noted that this work needs to be carried out in close collaboration with the designing of the different operational modules of the repositories (see Chapter 6.5) in order to properly characterise the operations and conditions in a repository and to provide feedback from operational safety aspects into the process of designing the various surface and underground facility modules, defining operational procedures and waste acceptance requirements.

6.4 Radioactive waste and materials

6.4.1 Waste inventories, characterisation, databases and logistics

Objectives of work – To improve estimates of radionuclide inventories in waste forms, focusing on those radionuclides that contribute most to dose and to provide complete waste characterisation data for all waste types, so as to provide databases to support the design of the repositories and analysing operational and long-term safety aspects for repositories for SF/HLW/ILW and L/ILW for different milestones. Where necessary, tools and methodologies to permit improved characterisation of various wastes will be further developed. In addition, concepts for logistics of waste packaging need to be further developed.

Status of work – A well-developed database is available on all waste types (Nagra 2008f). This database is based on the assumption of 50 years operation of existing nuclear power plants and the arisings from medicine, industry and research for the period up to 2050. Alternative waste inventories have also been developed for a prolonged operation period of existing nuclear power plants and for the assumption of additional power plants being constructed and a prolonged period for collecting waste from medicine, industry and research. The information includes key safety-relevant data for each waste type, including radionuclide inventory, quantities and composition of the various inorganic and organic materials and quantities and surface area to mass ratios of metals and alloys. The database provides a basis for calculating radionuclide release, production of gases arising from corrosion and decomposition of organics and the evolution of near-field chemistry. Various methods (measurement, calculation, and correlation, as well as documentation from the waste producers) are used to estimate the concentrations of radionuclides in the various waste types. The results provide average and upper limit estimates of radionuclide inventories as well as other key safety-relevant waste properties (inputs for spent fuel dissolution / instant release fractions, glass dissolution).

For waste packaging logistics, the SIMAN code (Simulated Annealing) has been developed for optimising loading arrangements of spent fuel assemblies, in order to comply with the maximum heat output criterion for a SF canister at the time of emplacement in the repository.

Focus of work – The work to be carried out focuses on the following aspects:

- *Improvement of radionuclide inventories for L/ILW* – The correlation factor method is used for the inventorying of the majority of the operational waste from the nuclear power plants (resins, sludges, …), complemented periodically with new measurements. The focus will be on the investigation of the time dependence of the correlation of difficult to measure to key nuclides and the influence of different types of fuel (UO_2 and MOX). For neutron activated in- and ex-core components, codes for 3D-mapping of energy dependent neutron fluxes will be developed as a basis for realistic activation calculations for exchangeable reactor components and decommissioning waste. In cooperation with the producers of research waste from accelerators, methods for the characterisation of waste activated by primary and secondary radiation other than neutrons will be further developed. The methods for inventorying of primary materials in wastes will be modified to provide application-oriented data for safety assessments (e.g. inputs to near-field release codes and chemotoxicity data).

- *Improvement of estimates of radionuclide inventories for ILW and HLW from reprocessing* – In support of this aim, Nagra will continue to work with waste producers to enhance the information base on the various waste types arising from reprocessing, including radionuclide and other materials inventories and their associated uncertainties.
- *Characterisation of SF* – The focus will be on improvement of methods for (high) burnup calculations for UO_2 and MOX for PWR and BWR fuel. In the area of burnup credit for PWR and BWR fuel, tools and methodologies will be further developed to support implementation of a criticality strategy. The SIMAN code for optimising the packaging of SF into disposal canisters will be improved and extended to consider the mixing of PWR and BWR fuel and the transfer of fuel from limited numbers of transport casks to disposal canisters.
- *Estimates of waste quantities and associated radionuclide inventories for potential generation III and IV power plants* – Information will be collected on Generation III and IV reactors in relation to the types and quantities of waste expected to be produced.

6.4.2 Waste conditioning and advice to waste producers

Objectives – To ensure that waste acceptance requirements are met and, where necessary, to further develop approaches for waste conditioning. Waste acceptance requirements provide the approach by which guidance can be given on waste treatment for new waste streams and through which changes in current waste treatment practices can be promoted.

Status – Research and development for waste matrices and waste conditioning for L/ILW is based on the internal waste acceptance requirements and on the regulations of HSK (HSK 2007). Compliance with the requirements is assessed within the procedure for obtaining a Disposability Certificate, including quality control programmes to verify important product parameters. With regard to potential modification of waste conditioning practices, a literature study has been completed to assess industrial methods for reduction or elimination of organics in L/ILW.

Focus of Work – Understanding of the chemical and chemotoxic characteristics of radioactive wastes will be improved and possibilities of reducing amounts of organics and/or treatment of organic materials as well as metals in radioactive waste will be investigated. This also includes investigation of melting of metals to improve the surface to volume ratio. The impact of conditioning methods on waste properties will be investigated in the context of safety assessment and the waste acceptance criteria updated if necessary. On request, Nagra provides support in evaluation of waste conditioning methods and support to build up and maintain methods for waste product control.

6.4.3 Improving understanding of safety-relevant characteristics of wastes

6.4.3.1 Spent fuel properties

Spent fuel – Instant release fraction (IRF) and matrix dissolution

Objectives of work – To improve the understanding of the behaviour of spent fuel (UO_2 and MOX) in the repository environment, such that models that describe the time-dependent release of radionuclides after canister breaching can be improved. This includes understanding the release of radionuclides from the fuel matrix and from the fuel/sheath gap (the instant release fraction, or IRF).

Status of work – The oxide matrix of spent fuel is expected to immobilise most of the radionuclide inventory for long enough that substantial decay will occur. The corrosion rate of the oxide matrix is very low under the reducing conditions in a repository and high concentrations of H_2 appear to make an important contribution to maintaining low dissolution rates (see, for example, Cui et al. 2008). The mechanistic explanation for the role of H_2 in suppressing the dissolution rate is not well understood and is the focus of modelling studies in the EU MICADO[55] project (Johnson et al. 2008) and experimental studies in the EU NF-PRO project (Grambow et al. 2008).

A small fraction of the radionuclide inventory is rapidly released on exposure to water (the instant release fraction or IRF). Updated estimates of the IRF for spent fuel of various burnups were made as part of the EU SFS[56] project (Johnson et al. 2005). In the study, it was noted that there were few measurements of the IRF for higher burnup fuels (> 50 GWd/tU). The possible increase of the IRF over time as a result of solid state diffusion processes has been studied within the EU NF-PRO project. This process was considered to have the potential to lead to larger grain-boundary inventories of radionuclides over time, which could then potentially contribute to the IRF. The results of the studies show that the diffusion coefficients are too low for this process to contribute to release even over the long term (10^5 to 10^6 years) (Grambow et al. 2008). Important progress was also made in the area of assessing the He pressure in gas bubbles in the fuel. This process was examined because He arising from decay of actinides will gradually accumulate in gas bubbles in the fuel, potentially increasing pressures to a level that could cause cracking. The studies indicate that this is not expected to occur for UO_2 fuel, but the situation for MOX fuel is less clear, thus further study may be required (Grambow et al. 2008).

Safety assessment calculations for Project Entsorgungsnachweis (Nagra 2002c) indicate that the IRF of spent fuel leads to the dominant radiological dose contribution. The relative contributions of matrix dissolution and IRF to radiological doses were examined by Johnson & Schneider (2007) in a sensitivity analysis study. The results show that matrix dissolution is unlikely to make the dominant contribution to dose, although sensitivity analyses have indicated that, if relatively high matrix dissolution rates arising from radiolytic oxidation were to occur, contributions to the (still low) total dose from fuel matrix dissolution would also become more significant. As noted above, oxidative dissolution is not considered to be realistic, thus it is now considered that the fuel matrix will have a very low dissolution rate and the IRF will dominate the radiological consequences.

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55 MICADO: Model uncertainty in the dissolution of spent fuel (EU project).

56 SFS: Spent Fuel Stability (EU project).

Based on current understanding, reduction of the uncertainties in some areas would contribute to providing increased confidence in the safety assessment. These include:

- an improved mechanistic understanding of SF matrix dissolution, in particular the role of radiolysis and hydrogen on the corrosion rate, and
- an improved database for the IRF of spent fuel, for the full range of expected fuel burnup values, but in particular for higher burnup values.

Focus of work – Nagra will continue to work closely with other organisations that are studying SF matrix dissolution. Specific aims of future work are to further develop models and databases for release of radionuclides from spent fuel. Some of these studies are being done through participation in the EU MICADO project. This project will be completed in 2009 and will provide a comprehensive review of spent fuel dissolution models and their associated uncertainties. Following completion of this study, work on model development is planned to continue through collaboration with various waste management organisations that are active in this area. The work will be focused on developing a model to be used in the safety assessment for the general licence application.

In order to develop a better understanding of the IRF for higher burnup fuels, Nagra is working with PSI and SKB to measure the IRF of UO_2 and MOX fuels with burnup values of ~ 60 GWd/tIHM, in the range of the average burnup values for spent fuel from nuclear power plants in Switzerland.

Behaviour of Zircaloy cladding

Objectives of work – To characterise the key repository-related materials performance aspects of Zircaloy fuel cladding. Issues of relevance include the rate of anaerobic corrosion and the rate of release of radionuclides, in particular ^{14}C and its speciation (note also that highly compacted Zircaloy hulls and ends comprise part of the fuel reprocessing waste). From the perspective of acceptance requirements, the utilities are responsible for guaranteeing the integrity of fuel assemblies upon their retrieval from storage casks for encapsulation in final disposal canisters. Nonetheless, Nagra continues to maintain an awareness of the issue given the importance of integrity in relation to fuel encapsulation and retrieveability.

Status of work – If hydride-induced cracking of Zircaloy cladding occurs in sealed disposal canisters, the barrier function of cladding would be lost in relation to preventing release of radionuclides under repository conditions, although releases could begin only after disposal canisters are breached by corrosion. Canister breaching is expected to take at least ten thousand years. The prospects for applying the present data on cladding integrity to time periods of hundreds or thousands of years is considered poor, because of uncertainties regarding various factors influencing hydrogen-induced cracking, such as the number of stress raisers (e.g. notches or incipient cracks) and crack growth rates. Consequently, the cladding was not given credit for confinement in the long-term safety assessment for Project Entsorgungsnachweis (Nagra 2002c). This is in agreement with the approach taken by other organisations (see, e.g., SKB 2006b).

Regarding radionuclide release from Zircaloy cladding in groundwater, the corrosion rate of Zircaloy is very low (Johnson & McGinnes 2002), thus release of long-lived neutron activation products such as ^{14}C and ^{36}Cl would be expected to be likewise low. There is, however, some evidence for enhanced release of ^{14}C from Zircaloy cladding (Yamaguchi et al. 1999), which is at present not well understood.

Focus of work – Regarding corrosion of Zircaloy and release of ^{14}C, some work is being done in conjunction with the high burnup fuel studies discussed in the above section on spent fuel properties. In addition, the scope and approach for a programme related to chemical speciation of ^{14}C and its behaviour in the repository environment is being developed in conjunction with PSI. It is expected that a laboratory programme will be pursued over the next few years.

6.4.3.2 Criticality assessment

Objectives of work – To assess the potential for criticality in a repository for spent fuel and to ensure that analysis and design measures comply with the requirement for sub-criticality in a repository.

Status of work – The approach of using burnup credit for spent fuel as a basis for demonstrating sub-criticality of spent fuel disposal canisters was adopted in Project Entsorgungsnachweis (Nagra 2002c). This approach is widely used and clearly has the potential to provide sound arguments for sub-criticality, but needs further development. Information exchange with other waste management organisations is ongoing (Johnson 2006). It is generally acknowledged that the nuclear criticality codes are sufficiently well developed and that the main uncertainties regarding maintenance of sub-criticality are related to uncertainties regarding the geometry of evolution of a breached disposal canister, including the degradation mode of the fuel assemblies.

Focus of work – The application of burnup credit approaches in international studies will be monitored and cooperative studies will be performed in conjunction with other waste management organisations. Further work will be done to define the conditions expected to arise in breached spent fuel canisters, including, for example, formation of corrosion products and mechanical degradation of fuel assemblies. The development of codes and databases for criticality calculations is covered under Section 6.4.1.

6.4.3.3 High-level waste glass corrosion

Objectives of work – To improve mechanistic understanding of the behaviour of HLW glass in the repository environment, such that improved models can be developed for long-term safety assessment that describe the time-dependent release of radionuclides after canister breaching.

Status of work – The HLW glass is expected to immobilise and retain most of the radionuclide inventory for long enough that substantial decay will occur. There is, in general, a reasonably good understanding of the characteristics of HLW glass. Nagra participated in the EU NF-PRO project, in which the status of understanding of HLW glass dissolution and of dissolution models used in safety assessment was most recently updated (Grambow et al. 2008). The main processes can be described in the following way:

- There is an initial high dissolution rate of the glass matrix.
- Glass constituents accumulate in solution (Si, Al and various alkali and alkaline earth species).
- Some of the less soluble glass constituents form a surface layer of reaction products on the glass (including formation of an underlying "gel layer").
- Reaction rates decrease due to the accumulation of dissolved silica in the aqueous phase adjacent to the dissolving glass or within the porewater of the gel.

- The rate gradually decreases to the residual reaction rate which can be up to 10'000 times lower than the initial rate.
- The decline to the residual rate may be retarded by adsorption of dissolved silica on iron corrosion products such as magnetite or on bentonite.

The main remaining uncertainties in determining the long-term glass dissolution rate under repository conditions are associated with the long-term extrapolation of laboratory data, in particular the residual dissolution rate.

Focus of work – The specific aim of future work is to address knowledge gaps related to glass dissolution (e.g. regarding the influence of clay minerals and especially iron corrosion products on Si sorption and hence Si concentration at the dissolving surface) and enhance support for the long-term dissolution rate assumed in safety assessment (Curti et al. 2006). Long-term dissolution experiments have been in progress at PSI since the 1980s and these will continue. It is planned to critically review the data developed within the EU NF-PRO project and elsewhere and examine the need for further experiments at PSI, including the possibility of further international collaboration in this area.

6.4.3.4 Gas Production

Objectives of work – To quantify the specific gas production rates of various materials present in wastes (in particular in L/ILW) and used in construction of engineered barriers (e.g. L/ILW containers and SF/HLW canisters). The gases produced include CH_4 and CO_2 from degradation of organic materials in wastes and H_2 from corrosion of various metals. The inventories of the various materials and the specific characteristics relevant to gas production (e.g. surface areas of metallic materials in L/ILW and the quantities and types of organic materials) are developed within the radioactive waste and materials programme (see Section 6.4.1). Furthermore, an evaluation will be made to investigate the possibilities to reduce overall volumes of gas generated and the generation rates (treatment of organics, melting of metals, etc.)

Status of work – The specific gas production rates of various metals and alloys present in wastes and used for construction materials in the HLW repository were reviewed as a basis for performing the safety assessment for Project Entsorgungsnachweis (Nagra 2002d, Nagra 2004). For the study of the effects of gas generation in the context of siting a repository for L/ILW in Opalinus Clay (Nagra 2008g), Nagra's proposed specific gas production rates and supporting references for the rates were reviewed by external experts. The review indicated that the specific gas production rates for metals selected by Nagra are realistic, although they may be slightly overestimated. For gas production as a result of decomposition of organics, the external review considered that the rates may be significantly overestimated, although the complexity of the waste makes it difficult to make more realistic assumptions regarding the gas production rate. It is noted that the overall volume of gas produced due to decomposition of organics in L/ILW is less than 10 % of the total gas produced in a L/ILW repository for the waste inventory for current NPPs assuming a 50 years operation time. However, because the contribution of organics to the gas generation rate is significant in an intermediate period (see e.g. Nagra 2008g) and to reduce the complexity introduced due to organics (gas generation, complexants, etc.) it seems justified to reduce the amount of organics as far as reasonably feasible.

For the option of SF/HLW canisters constructed from carbon steel, the rate of hydrogen generation as a result of anaerobic corrosion in bentonite has been reviewed by King (2008) and Landolt et al. (2009). The rate adopted in the safety assessment of Project Entsorgungsnachweis (Nagra 2002c) was supported.

Focus of work – For most metals present in the wastes and used as construction materials, the gas production rate data for L/ILW repository conditions are considered relatively good and there is likely little need or benefit to further studying the corrosion rates. In the case of carbon steel corrosion in bentonite, the impact of the aerobic phase of the repository evolution (the first few decades after closure of the waste emplacement tunnels) on the subsequent anaerobic gas production rate will be studied, although the overall impact on the H_2 gas production rate is expected to be small.

The rate of decomposition of organic materials in L/ILW will be further evaluated through consideration of alternative approaches to modelling the kinetics and by considering results from various published experimental and modelling studies.

One aspect that is being studied further is the question of what fraction of organic ^{14}C released from metallic wastes (ILW, L/ILW) might be available in gaseous form.

6.5 Repository design concepts and engineered barriers

6.5.1 Development of generic design concepts and operation schemes (including retrieval of wastes)

Objectives of work – To develop reliable and robust generic facility modules and corresponding lay-out concepts which provide the design basis for the site-specific allocation and basic lay-out concepts of the surface facilities and the access to the underground facilities for the HLW and L/ILW repositories. The modules to be further developed include those on the surface (access, waste receiving and handling facilities, shaft head-frame and ramp access) and underground (construction and operations tunnels, pilot repository, waste emplacement rooms and underground test facility). This development also includes rock-mechanical considerations to evaluate suitable cross-sections, the importance of the orientation of the emplacement rooms/sealing sections in the in-situ stress field and suitable excavation/construction methods. The development of the modules also considers the different operational aspects, including retrieval of the wastes (see below). The modules provide the basis for the site-specific design concepts for the surface facilities as required in Stage 2 of the Sectoral Plan.

The requirement for retrievability demands that for the operational licence of a repository, the feasibility to retrieve the wastes with reasonable effort has to be demonstrated. Technology for retrieval will be developed and a demonstration of retrievability will thus be performed in the period prior to the repository operation licence (~ 2040 for HLW and ~ 2030 for L/ILW). For the period up to the general licence application, concepts will be refined with the objective to ensure that the retrievability requirement is adequately integrated into the conceptual design studies.

Status of work – A facilities *feasibility* study for a repository for SF/HLW/ILW in Opalinus Clay was presented in Nagra (2002b). Furthermore a *preliminary design* formed the basis for the general licence application for a repository for L/ILW (GNW 1994). The concepts for some of the elements of the facilities were in the meantime further developed. The concepts are discussed in Nagra (2008a) and Nagra (2008e). Furthermore, recommendations from the authorities referring to the feasibility study in Opalinus Clay (Nagra 2008b) provide valuable input to the HLW facility planning and optimisation and are partially already considered in the concepts discussed.

Retrievability concepts were developed for the L/ILW repository at Wellenberg (see Nagra 1998). An approach for retrieval of SF and HLW canisters from a HLW repository in Opalinus Clay was outlined in Nagra (2002b). This provides an adequate basis for further development.

Focus of work – In preparation for the Sectoral Plan Stage 2 and the general licence applications, the design studies are at the *conceptual level*. For Stage 2 of the Sectoral Plan the main boundary conditions and the potential for flexibility regarding allocation of the surface facilities, access to and arrangement of underground facilities are defined to ensure the overall feasibility of the sites to be proposed. This includes the development of robust conceptual designs of generic modules and concepts including alternative configurations for the different facility elements taking into account different boundary conditions. The focus is on the layout of the different elements of the underground facilities (cross-sections of emplacement rooms and of access facilities, shafts etc. for the different geological environments), surface facilities, ventilation system, construction methods, operation concept and specific aspects to ensure operational safety. For these aspects, geomechanical considerations are also included: cross-sections, orientation and construction methods for the waste emplacement rooms (incl. their direct access) are chosen to keep disturbances of the surrounding host rock within reasonable limits.

The requirement for retrievability of the canisters/containers is also incorporated into the basic requirements for future canister/container development and generic facility modules planning. For the general licence application, design studies concerning retrievability at the *conceptual level* are needed in order to describe the approximate layout of the underground and surface facilities. This includes the development of generic concepts and strategies for the whole retrieval chain which have to consider the range of possible in-situ boundary conditions that may exist at various retrieval times within the repository operational phase (e.g. geomechanical stability, temperature, etc.).

6.5.2 Adaptation of generic repository concepts to specific sites

Objectives of work – To provide a suitable basis of the surface and underground facilities for the HLW and L/ILW repositories for Stage 2 of the Sectoral Plan (basis for provisional safety analyses, input to socio-economic assessments) and to provide a conceptual design for the general licence application for the HLW and L/ILW repositories.

Status of work – A site-related facilities *planning and feasibility* study for the repository for SF/HLW/ILW in Opalinus Clay was presented in Nagra (2002b). Furthermore a site-related *preliminary design* formed the basis for the general licence application of a repository for L/ILW (GNW 1994). Some elements of the facilities were further developed (see Nagra 2008a and Nagra 2008e). The work described in Section 6.5.1 is well underway and will provide a suitable basis for the site-related conceptual designs for Stage 2 of the Sectoral Plan and for the general licence applications.

Focus of work – An overall framework for the continuing stepwise development of design concepts for the various phases of repository development has been prepared. Based on the modules to be developed (see Section 6.5.1) site-related repository conceptual design studies are developed that provide the basis as input for the involvement of the affected regions for making the decisions needed in Stage 2 of the Sectoral Plan. For the general licence application, *conceptual design* studies will be produced to progressively define more detail. This will involve developing the underground layout, including the test facilities, pilot facility (see also Section 6.5.5) and main facility and operations and construction tunnels and access from the surface (ramp and shaft(s)). *Basic design* work will begin after issuing of the general licence, with the initial focus being on access and infrastructure and ramp/URL design.

6.5.3 Development of concepts for the engineered barriers

The basic design concepts for repositories for HLW and L/ILW have been established as a result of developments associated with preparing the previously submitted safety reports for HLW (Nagra 2002b and c) and L/ILW (GNW 1994). The concepts have been further developed in the meantime (see e.g. the summaries in Nagra 2008a).

6.5.3.1 Development of SF and HLW canisters

Materials evaluation for SF/HLW canisters

Objectives of work – Canisters will have to be designed, constructed, and demonstrated to meet facility licensing requirements by ~ 2040. This provides a long period for stepwise evaluation of materials and technology possibilities. The intention is to have SF and HLW canister design concepts developed for the general licence application (~ 2015), leaving materials options open, to continue development studies in the period ~ 2015 – 2025 and to select the final canister designs in ~ 2025. Detailed development and optimisation would continue over the subsequent 10 to 15 years, during which time canister emplacement technology would be developed and tested in the test facility at the repository site. For the general licence application, the main objectives in materials evaluation are to have more than one material option available, including the basis for describing long-term performance of these materials, to have a good overview of worldwide developments in materials performance and evaluation issues and to have sufficient information to provide guidance for a design study for carbon steel canisters for SF and HLW (see below, technology development for SF/HLW canisters).

Status of work – Both carbon steel and copper/cast iron canister design concepts were adopted for Project Entsorgungsnachweis and canister lifetimes of > 10'000 years for steel canisters and > 100'000 years for copper canisters were projected (Johnson & King 2003). The basic materials properties including uniform and localised corrosion and processes such as stress-corrosion cracking are quite well understood for both carbon steel and copper, although there are areas in which further work should be done to improve understanding. An important issue in the review of Project Entsorgungsnachweis was the gas production arising from the anaerobic corrosion of carbon steel canisters used in the reference design. Because of the importance of this issue and the recognition that a broad review by external experts would be valuable, Nagra established a Canister Materials Review Board, an independent group of corrosion experts that is providing advice on materials evaluation and selection. The Review Board has met several times and has completed a report (Landolt et al. 2009) that gives recommendations regarding materials selection options and future studies. Nagra is pursuing a dual path on the gas issue, in that the gas transport implications for an Opalinus Clay repository with steel canisters will continue to be evaluated, concurrently with study of alternative canister options (in particular copper/cast iron), where gas production is greatly reduced. In the context of the work of the Review Board, the rate of anaerobic corrosion of carbon steel was further evaluated by King (2008), including consideration of the impact of the early stages of evolution of the canister surface under disposal conditions.

Focus of work – Further work related to corrosion will be defined based on input from the Canister Materials Review Board (Landolt et al. 2009). This will include an assessment of hydrogen effects and post-weld residual stresses on the mechanical properties of carbon steel. In addition, the significance of sulphide corrosion will be examined. Additional studies of coupled TH modelling of the resaturation transient are also being pursued (Senger & Ewing 2008, see Section 6.5.4.2.4), to better define the temperature and moisture evolution at the canister surface and thus the conditions for localised and uniform corrosion (Johnson & King 2008). An evaluation of the expected corrosion performance of copper for the porewater chemistry conditions of a repository in Opalinus Clay will also be performed. As noted below, Nagra will monitor developments in relation to ceramic materials, in particular aspects having a bearing on fabrication and construction feasibility.

Technology development for SF/HLW canisters

Objectives of work – The objective is to have canister design concepts for SF and HLW available for the general licence application (with options still remaining open), to continue development studies in the period ~ 2015 – 2025 and to select the final canister designs in ~ 2025. Detailed development and optimisation would continue over the subsequent 10 to 15 years, during which time canister emplacement technology would be developed and tested in the URL at the repository site.

Status of work – A design for carbon steel HLW canisters was developed in the 1980s for Project Gewähr (Nagra 1985). Both carbon steel and copper/cast iron canister design concepts were adopted for Project Entsorgungsnachweis and canister lifetimes of > 10'000 years for steel canisters and > 100'000 years for copper canisters were projected. For steel canisters, only preliminary feasibility assessment studies were performed and no welding or inspection studies were performed. For canisters for HLW, thermal optimisation studies show that it is feasible to place two HLW flasks in one disposal canister and this will be taken into consideration in a future design study**.**

Focus of work – Following on from the materials selection studies noted above and the advice of the Canister Materials Review Board, a review will be performed of the present state of technology for welding thick-walled carbon steel, including the assessment and reduction of residual stresses. This will be followed by a design study for carbon steel canisters for both SF and HLW. For copper/cast iron canisters, the studies by SKB and Posiva will be closely followed. Both carbon steel and copper/cast iron design options will be considered in the general licence application, pending further assessment of the gas issue. Work on possible application of alternative materials for canisters that might have substantially lower gas production rates (e.g. very low corrosion rate metals and ceramics) will be followed, with particular emphasis on technological feasibility issues.

6.5.3.2 Development of L/ILW disposal containers & container backfill material

Objectives of work – The objective is to have a design concept for the L/ILW disposal containers available for the general licence applications for the L/ILW repository and for the HLW repository[57]. The detailed design has to be ready for the construction licence. According to the current concepts, these containers will be made out of concrete. The containers loaded with waste packages are backfilled with a cementitious mortar.

Status of work – Concrete containers are manufactured today on a routine basis. Also for disposal purposes concrete containers have been successfully fabricated and are regularly used e.g. by PSI for packaging of waste from medicine, industry and research (canister types KC-T12/30 and GC-T24). Backfill materials have also been developed and are regularly used.

Focus of work – For the general licence application a conceptual design for the container and the backfill will be developed that considers all the requirements. This includes aspects of operational safety, retrievability and long-term safety.

6.5.3.3 Backfill materials and emplacement technologies for waste emplacement tunnels and caverns

6.5.3.3.1 Buffer material evaluation for HLW emplacement tunnels

Objective of work – The reference material MX-80 has been chosen by various waste management organisations and the status of characterisation and studies is correspondingly advanced. It is recognised, nonetheless, that bentonites other than MX-80, that contain similarly high montmorillonite contents, are likely to ultimately be used in the final repository for reasons related to availability and cost. The objective of the work is thus to identify various suitable bentonite materials for use as buffer material around SF/HLW canisters in relation to the requirements (swelling, hydraulic conductivity) and to demonstrate how the knowledge base on MX-80 bentonite would be transferred to these materials. A reference material will be selected for the general licence application. Alternatives will be evaluated and options regarding the final selection of buffer material should remain open until the period leading up to the nuclear construction licence application, to take advantage of ongoing developments. Included in the alternatives studies are investigations of bentonite/sand mixtures (80/20 or 70/30), which could increase both thermal conductivity and gas permeability.

Status of work – No specific work has yet been done by Nagra on selecting alternative bentonites. There is, however, considerable information available on bentonite resources and compositions, including the work by other waste management organisations. There is also a good basis for selecting suitable bentonites based on montmorillonite content and accessory mineral contents.

Focus of work – Information will be reviewed regarding the various bentonites that are available in relation to resources, availability, composition and cost. An overall methodology for selecting bentonites that would meet the safety and design requirements will be developed. Information exchange with other waste management organisations will be pursued. Part of the task will involve reviewing the transferability of the knowledge developed on safety-related characteristics (diffusion, sorption, hydraulic conductivity, thermal properties, etc.) of MX-80 bentonite to these alternative bentonites.

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[57] In the HLW repository, such disposal containers are used for the long-lived ILW.

6.5.3.3.2 Buffer emplacement technology

Objectives of work – To develop and demonstrate that appropriate methods exist for emplacing the buffer material around the SF/HLW canisters, with which acceptable densities can be reached with equipment that is practical for remote operation. The repository implementation date permits considerable time for development. As with the case of canister development, a reference concept of emplacement must be developed for the general licence application. The final design will be made for the construction licence. Tests of the method chosen are expected to be performed at the underground laboratory at the disposal site.

Status of work – The emplacement method for the present reference material (MX-80 bentonite in highly compacted granular form combined with bentonite blocks to support the canisters) has been developed and technology for material preparation and emplacement has been tested in the laboratory, in the EB experiment in Mont Terri (Mayor et al. 2007a) and in a mock-up tunnel at full scale as part of the ESDRED project (Plötze & Weber 2007). Appropriate average emplacement dry densities (1.45 to 1.5 $Mg\ m^{-3}$) were achieved in the ESDRED large-scale tests. Bentonite block fabrication technology is already well established as a result of SKB studies (SKB 2007a). Work on compaction at small scale has included bentonite/sand mixtures (see Section 6.5.3.3.1).

Focus of work – For the next several years, the work will include re-evaluation of the requirements for the buffer, reviewing options, including the types of bentonite available, the viability of mixtures of bentonite and sand and further improvement of emplacement technology. More experience will be gained in relation to emplacement technology with the planned EU PEBS project and later with the proposed 1:1 heater/buffer studies at Mont Terri (see also Section 6.5.4.2.4).

6.5.3.3.3 Technology and materials for SF/HLW emplacement tunnel support/liner

Objectives of work – It is necessary to have suitable materials and technology available for proving adequate support of HLW emplacement tunnels for the stress state and geomechanical boundary conditions also for those candidate sites for a HLW repository in Opalinus Clay where higher rock stresses are expected (e.g. due to higher overburden). Under good conditions, it is possible that only rock bolts and mesh will be required; however, it is considered prudent to develop approaches that are suitable for less favourable conditions and are compatible with both operational and long-term safety requirements. In selecting materials and methods, consideration needs to be given to the requirements to minimise alteration of the buffer and to avoid increased gas production. As a result, high pH cement and massive steel liners are preferably avoided because of potential detrimental impacts. Alternative materials such as low pH shotcrete or special resin type protection layers (e.g. Mine-guard) should be tested. In addition, questions regarding the optimum interaction between construction method, tunnel lining and support dimension as well as timing for support implementation have to be investigated, in order to reduce progressive failure and formation of a large EDZ and to avoid overstressing of the liner leading to support failure.

Status of work – Low pH cement has been successfully tested for shotcrete application during the ESDRED project in the laboratory and in field tests (Fries et al. 2007). Other alternative materials for tunnel support are used in very deep mines in Canada and South Africa but so far limited work is available from nuclear waste disposal programmes. Large-scale tests on tunnel support / liner have been performed during tunnel construction at the Mont Terri URL. During these excavations, the first application of low pH shotcrete has been made and the results are being monitored.

Focus of work – Further large-scale tests on tunnel support / liner are being performed at Mont Terri (SB experiment in conjunction with the tunnelling performed in 2008). The combination of tunnel support, monitoring and a mine-by test has been advantageous during the excavation of the gallery 08 at Mont Terri. These tests will improve the process understanding and data base of geomechanical/rock support interactions and allowed testing of alternative materials (e.g. low pH cement). Conceptual design studies will be carried out to develop alternative tunnel lining and support designs as well as to define optimised construction methods. The safety requirements will be incorporated into the design studies, including assessment of interactions of low pH shotcrete with bentonite (see Section 6.5.4.2.2).

6.5.3.3.4 Cement-based backfills for L/ILW emplacement caverns

Objectives of work – To develop cement-based grouting materials for backfilling L/ILW emplacement caverns[58]. For the general licence application concepts for backfill grouts must be available.

Status of work – Various cement-based grouts have been developed in the context of the technical studies for Wellenberg (e.g. Jacobs et al. 1994, Mayer & Wittmann 1996). It is considered that the technology for grouts is fairly well developed, but a re-evaluation will be done to select specific grouts for the present design concepts.

Focus of work – The requirements for the backfill grouts will be re-evaluated, based on the requirements from long-term safety, technological feasibility, operational safety and retrievability. Based on these requirements, a study will be performed to survey the materials presently available that could meet these requirements and to identify further development work needed.

6.5.3.3.5 Repository sealing and closure

Objectives of work – To design, develop and test reliable long-term seals of emplacement, operations and access ramp and shafts which can withstand the necessary fluid and/or gas pressures and maintain acceptably low hydraulic flow. The sealing system includes various sealing elements and their associated mechanical confinement, each of which has to fulfil different functions. The specific sealing elements include: i) temporary seals[59], ii) long-term seals of low permeability, iii) seals with sufficiently high gas permeability to keep gas pressures at an acceptably low level in disposal caverns (L/ILW), while still maintaining sufficiently low solute transport and iv) backfill materials for access tunnels, shafts and the access ramp.

Backfilling techniques for reliable closure of all underground openings have to be designed and tested to keep long-term convergence of the backfilled tunnels at acceptable levels and to prevent human intrusion into the closed repository while providing good retention properties for radionuclides (sorption).

Status of work – Design concepts for repository sealing were presented in Sitz (2002). Laboratory and in-situ investigations have been carried out to investigate sealing systems for boreholes (Blümling & Adams 2008) and tunnels (Mont Terri SB experiment). Water and gas permeability of different sealing materials are under evaluation (SB experiment). Additional information is expected from the analysis of the Mont Terri experiments HG-A and EB.

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[58] This backfill will also be used in the HLW repository for backfilling the ILW emplacement tunnels.

[59] According to the regulatory guideline G03 (ENSI 2009), seals must be available that can be emplaced within a short time; however, these seals must not be permanent.

Investigations on the effect of a specially designed key zone where the EDZ has been partly removed (EDZ cut-off) were conducted as part of the EDZ-A[60] experiment at Mont Terri.

Contacts with the salt mining industry in Germany have been established to get first-hand information on sealing technologies of shafts and tunnels in salt rock.

The requirements for the various types of seals are currently being evaluated, although some preliminary requirements for long-term hydraulic seals were adopted for the study of Sitz (2002) and for Project Entsorgungsnachweis (Nagra 2002c). For evaluating the requirements for seals that allow the gas to escape at reasonable overpressures, the design calculations such as those documented in Nagra (2008g) provide a suitable basis.

Focus of work – The requirements for seals from the perspective of long-term safety will be further developed. Design studies (incl. material evaluation) will be carried out to further develop the necessary sealing and backfilling concepts and techniques. These studies will be accompanied by detailed modelling to investigate the sensitivity of the sealing system to mechanical and hydraulic loading and gas transport. Thus, a comprehensive laboratory programme will be conducted as part of the EU FORGE project, aimed at characterising the THMC behaviour of sand-bentonite mixtures with low bentonite content. In addition, modelling will be carried out to evaluate the performance of the sealing concepts with respect to radionuclide transport and their sensitivity e.g. to high pH-fluids (see also Section 6.5.4.2.2).

A large-scale sealing experiment is planned at the Mont Terri laboratory to test the most promising seal design and sealing material. The experiment will include design work and modelling. After saturation of the sealing system mechanical, hydraulic and gas tests will be performed to evaluate the efficiency of the seal.

6.5.4 Improving understanding of safety-relevant properties and processes in the near-field, the engineered barriers and in compacted clay systems

6.5.4.1 Immobilisation, retardation and transport phenomena for radionuclides in compacted clay systems and cementitious materials

Objectives of work – To provide reliable data for safety assessment and corresponding understanding of transport and chemical retention processes in clay-rich host rocks[61], bentonites and cement-based materials as a necessary basis for the safety reports required at each milestone in the Swiss waste management programme. These data and understanding must reflect the state of the art at each milestone. Chemical retention processes for radionuclides include sorption, surface precipitation, solid solution formation and solubility limitations. The understanding of chemical in-situ conditions and their temporal evolution is a prerequisite for the characterisation of chemical retention processes in the barrier systems and is therefore also an objective of work. This includes the development of thermodynamic data bases used to calculate pore water composition and aqueous speciation of radionuclides (including redox) and takes into account other potential influencing factors (e.g. corrosion of steels). Parts of the content of Section 6.2.4.1, dealing with retention properties of the host rock, are repeated here for clarity.

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[60] EDZ-A: EDZ cut-off (Mont Terri experiment).

[61] Because the retardation processes in clay-rich rocks and bentonite are analogous, they are discussed together in this section.

Status of work – Compacted clay systems such as bentonites and Opalinus Clay are shown to provide a highly effective barrier to radionuclide transport (see, e.g., documentation for Project Entsorgungsnachweis, numerous reports by PSI). Multiple lines of argument are available to show that the slow process of diffusion is the controlling transport mechanism within compacted clay systems. Transport within compacted clay systems is further retarded by sorption, which has been extensively studied at PSI (Van Loon et al. 2005, Van Loon et al. 2009). In the area of understanding of diffusion processes of weakly sorbing and non-sorbing tracers, there is good agreement between laboratory and field experiments (see, e.g. Van Loon et al. 2004, Wersin et al. 2008), as discussed in Section 6.2.4.1.

For Project Entsorgungsnachweis, comprehensive K_d databases for Opalinus Clay (Bradbury & Baeyens 2003a), bentonite (Bradbury & Baeyens 2003b) and cementitious materials (Wieland & Van Loon 2002) were derived, based largely on laboratory batch sorption experiments on dispersed systems. These data were extrapolated to in-situ conditions and used to calculate radionuclide transport in compacted systems. Gaps in the database were filled using data from the scientific literature and chemical analogy arguments. Diffusion experiments and batch sorption tests on compacted materials are being carried out to confirm the transferability of sorption values from dispersed to compacted systems (Van Loon et al. 2005, Van Loon et al. 2009). Also, for Stage 1 of the Sectoral Plan, where the issue was to evaluate different host rock types, sorption data bases for generic argillaceous, crystalline and calcareous rock systems were developed (Bradbury et al. 2008). In that study, work done for the Wellenberg project (Bradbury & Baeyens 1997c) also provided important information.

The clay minerals montmorillonite and illite are primarily responsible for the uptake on bentonites and argillaceous rocks respectively. Mechanistic sorption models have been developed for these two clay minerals which can quantitatively describe radionuclide uptake over a wide range of conditions (Bradbury & Baeyens 1997a, Bradbury & Baeyens 2009a, b). Linear Free Energy Relationships (LFER) between surface complexation constants and the corresponding hydrolysis constants have been established for montmorillonite and illite allowing poorly or unknown surface binding constants to be obtained (Bradbury & Baeyens 2004, Bradbury & Baeyens 2009b). These LFER are regarded as an important component in the development of sorption data bases founded on thermodynamic principles to be used for deriving sorption databases for bentonite (or bentonite-sand mixtures) and for the different clay-rich host rocks.

The developed mechanistic sorption models have been imported into the reactive transport code MCOTAC (Pfingsten 1994). This development allows radionuclide migration calculations to be carried out in which, for example, sorption competition is included or in which time and temporally evolving in-situ conditions can be simulated (Jakob et al. 2009).

Extensive work on sorption of radionuclides on cementitious materials in the L/ILW repository near-field was used for the Wellenberg project (Bradbury & Baeyens 1997c, 1997d). This material and further work was also used for Project Entsorgungsnachweis (Wieland & Van Loon 2002).

For many relevant radionuclides, solubility control by amorphous hydroxide phases was assumed in Project Entsorgungsnachweis for both the SF/HLW (Berner 2002) and L/ILW near-field (Berner 2003). The assumption of crystalline phases or solid solutions would have led to much lower aqueous concentrations but their existence in reality is not proven. Co-precipitation and solid solution formation may be effective immobilisation processes, but their significance is difficult to quantify for most elements because of limited thermodynamic data on the phases formed and slow kinetics.

Comprehensive progress reports of the extensive studies performed by PSI's Laboratory for Waste Management are published on an annual basis (see, e.g., PSI 2008).

Focus of work

Laboratory and field diffusion experiments on clay minerals and compacted clay systems (relevant for Opalinus Clay and other clay-rich potential host rocks as well as bentonite and bentonite/sand mixtures) are conducted in collaboration with PSI (Van Loon et al. 2003, Van Loon et al. 2004, Van Loon et al. 2005). The diffusion of strongly sorbing di-, tri- and tetravalent species is being studied in the laboratory and also for selected metal species at the Mont Terri URL (the DR[62] experiment). The diffusion/retention data at different scales (e.g. Van Loon et al. 2003, Van Loon et al. 2004), including natural tracer profiles (Gimmi et al. 2007), are generally analysed with a simple Fickian diffusion model. However, the current trend is towards the use of reactive transport codes containing more complex geochemical models (Appelo & Wersin 2007, Jakob et al. 2009) (see below) in which effects that may influence porewater composition and diffusion-accessible porosity are accounted for. In order to support diffusion experiments using strongly sorbing tracers, high resolution techniques for analysing narrow diffusion profiles are being developed at PSI, e.g. micro-XAS[63], Abrasive Peeling (Van Loon & Eikenberg 2005) and Laser Ablation-MS[64].

The diffusion in Opalinus Clay of small organic molecules incorporating ^{14}C is also being studied because there is some evidence indicating that such molecules may be released from some waste types (e.g. activated metals) during corrosion. Because of their low retention in compacted clay systems, this is a highly relevant issue in safety assessment. Diffusion of redox-sensitive radionuclides, e.g. Se (II, IV) and Tc (IV and VII) are currently under investigation; U (IV and VI) and Np (IV and V) will be addressed at a later stage.

Using the available generic data and the methodology developed, retention properties for the other potential host rocks will be updated/derived ('Brauner Dogger', Effingen Beds, Helvetic marls). The derived properties will be checked in a point-wise manner by experimental investigations of corresponding rock samples.

For bentonite, through-diffusion experiments with HTO, Cl, Na and Cs (e.g. Van Loon et al. 2007) have been carried out at PSI in order to validate sorption data obtained from batch sorption measurements and to better understand the effects of overlapping electrostatic double layers (EDLs) on the transport of Cl^- (anion exclusion) and other neutral species and cations in the interlayer space and external pore space. In-diffusion experiments with strongly sorbing species similar to those planned for Opalinus Clay are foreseen at a later stage.

Batch sorption experiments and associated experimental investigations are being carried out on clay minerals, Opalinus Clay and other potential host rocks, as well as bentonite, in order to:

- assess the impact of prevailing chemical conditions on diffusion/retention, including aqueous complexation (Marques et al. 2008) and sorption competition between different metal ions (Bradbury & Baeyens 2005), both of which are important for evaluating sorption in in-situ conditions
- reduce reliance on chemical analogues and literature data measured under different conditions or with different methodologies

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62 DR: Radionuclide Diffusion and Retention (Mont Terri experiment).

63 XAS: X-ray Absorption Spectroscopy.

64 MS: Mass Spectroscopy.

- assess the possible impact on retention of irreversible (or slowly reversible) processes such as radionuclide incorporation in clay mineral matrices, surface precipitation and the formation of solid solutions, and the validity of a K_d approach to sorption modelling in safety assessment, which is based on the assumption of equilibrium, reversible linear sorption.
- enhance fundamental understanding of sorption processes (as a basis for mechanistic modelling)
- identify surface species using advanced surface analytical techniques
- continue with the long term aim of developing sorption data bases founded on thermodynamic principles rather than just K_d values (NEA 2001 and 2005)

Further, some scoping experiments on the influence of temperature on sorption will be carried out to determine whether or not the effects merit more detailed investigations. Spectroscopic methods, such as XAS (Dähn et al. 2002 and 2003) and Time Resolved Laser Fluorescence (Rabung et al 2005, Tits et al 2003) will be used to elucidate the bonding of radionuclides to clay mineral surfaces. International collaboration in these areas has already been established by Nagra and PSI through participation in EU (ACTINET-I3[65], RECOSY[66]) and OECD/NEA projects. All this work is being done with a view to developing more realistic sorption data bases for safety assessment supported by a good mechanistic understanding of the associated processes.

Batch sorption experiments and associated experimental investigations on cement materials will continue to be conducted by PSI (Tits et al. 2003 and 2006, Wieland & Van Loon 2002, Wieland et al. 2006). Cementitious systems are characterised by high pH (12-13) and high reactivity and sorption, incorporation and solid solution formation are all important retention processes which can be determined using spectroscopic methods (XAS, TRLFS) (e.g. Bonhoure et al. 2006, Harfouche et al. 2006, Tits et al. 2003, Vespa et al. 2006).

The sorption and diffusion in cement of small organic molecules incorporating ^{14}C is being studied because the current evidence indicates that these may be released from activated metals during corrosion.

Molecular modelling studies will be performed in order to provide deeper, more fundamental understanding of transport in clay media (Kosakowski et al. 2008) and radionuclide uptake by cement (Churakov 2009). Furthermore this work provides a valuable link between spectroscopic studies and diffusion and batch sorption measurements (González Sánchez et al. 2008).

The Nagra/PSI thermodynamic database (Hummel et al. 2002) will be updated to support the restricted availability of radionuclides in solution through solubility limitations and to carry out speciation calculations and the modelling of porewater compositions. The objectives are to integrate new data identified, for example, from the OECD/NEA TDB Project, fill in relevant gaps in the data where possible and incorporate higher temperature data for relevant subsystems where these are available. In parallel, techniques are being developed to extrapolate thermodynamic data measured at 25°C to more relevant temperatures (50 – 60°C) and thus allow reliable thermodynamic modelling at these elevated temperatures. Work will also continue to develop a systematic means of evaluating the propagation of parameter uncertainties in calculated solubility limits, speciation etc. The updated thermodynamic data base, available temperature data and an uncertainty evaluation module are being implemented in GEMS (Gibbs Energy

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65 ACTINET: European Network for Actinide Sciences.

66 RECOSY: Redox phenomena controlling systems (EU project).

Minimisation Selektor), a code developed at PSI that allows simultaneous modelling of aqueous speciation, surface complexation (Kulik 2006), co-precipitation and solid-solution formation.

Studies of microbially-induced effects will be performed at Mont Terri and in laboratories at the University of Lausanne, including understanding the conditions under which microbial activity can occur (rock pore sizes, availability of nutrients, etc.), and assessing possible implications for repository performance, including redox effects, canister corrosion and radionuclide mobility.

6.5.4.2 Evaluation of the evolution of the near-field

Studies of the relevant near-field processes are being pursued in order to establish their impacts on long-term evolution of the near-field and on the relevant associated safety functions over the long term. In the context of the engineered barrier system, for the HLW repository these safety functions involve *confinement* in the long-lived canisters for SF and HLW and *attenuation of releases* as a result of slow dissolution of waste forms, and slow transport, including precipitation and sorption, through the clay and cement-based engineered barrier materials. For the long-lived ILW and for the L/ILW repository the main focus is on slow transport, including precipitation and sorption, through the cement-based engineered barrier materials and the clay-based sealing materials. In order to assess the long-term evolution of the near-field with respect to these phenomena, process understanding and modelling capabilities need to be further developed. Aspects related to radionuclide retention are discussed in Section 6.5.4.1.

6.5.4.2.1 Development of modelling capabilities for near-field resaturation

Objectives of work – The overall objective is to improve the modelling capabilities for resaturation of the near-field of HLW and L/ILW repositories. Resaturation of the repository sets the hydraulic framework for the temporal and spatial evolution of the emplacement tunnels and caverns and the disturbed system around them. In particular, it controls the onset of the bentonite backfill swelling process and gas generation in the backfilled disposal tunnels and affects heat transfer through the near-field.

Status of work – Resaturation has been addressed for the HLW repository in Project Entsorgungsnachweis (Nagra 2002a) and within the Wellenberg project (Nagra 1997). The improvement of modelling capabilities for the near-field saturation has recently again been a focal point in Nagra's programme. A review of the THMC processes in the near-field of a SF/HLW disposal system focusing on the resaturation transient was accomplished in the NF-PRO project as part of the EU 6th Framework Programme (Huertas et al. 2008). Modelling activities have been conducted to explore the resaturation transient for SF canisters in the non-isothermal early time when peak temperature is reached in the bentonite (Senger 2006, Senger & Ewing 2008). The results have been used to clarify the early stages of evolution of temperature and moisture conditions on the surface of disposal canisters, as input to assessment of canister corrosion. In relation to a potential L/ILW repository in Opalinus Clay, the modelling of resaturation has been performed in the context of a comprehensive study of gas production and transport (Nagra 2008g).

Focus of work – The details of the repository near-field resaturation are relevant for both the L/ILW disposal concept and the SF/HLW concept. The work programme includes (i) development of detailed system models of the repository near-field resaturation, (ii) development of coupled THMC modelling capabilities that incorporate the resaturation process, see Section 6.5.4.2.4, (iii) active participation in international near-field research programmes (projects within the EU 6th and 7th Framework Programmes such as TIMODAZ, PEBS and FORGE).

6.5.4.2.2 Key properties and long-term evolution of bentonite and clay-rich materials

Thermal effects on bentonite performance

Objectives of work – To improve the understanding of the impact of high temperatures (up to 150 °C) on the short- and long-term performance of bentonite regarding its safety functions (e.g. hydraulic conductivity, swelling pressure, retention qualities). This work is performed in order to support future design optimisation studies (specification of design requirements for the emplaced bentonite and thermal constraints for repository design) and long-term safety studies. As noted in Section 6.5.3.3.1, bentonite/sand mixtures are also being studied.

Status of work – Processes will occur in the transient thermal phase that have the potential to affect the retention safety function of the bentonite buffer. In particular, the swelling and hydraulic properties of bentonite may be affected by chemical alteration processes at high temperatures, thus influencing hydro-mechanical interaction with the host rock and the overall hydraulic and radionuclide transport characteristics of the near-field. According to recent coupled TH modelling calculations of Senger & Ewing (2008), the maximum temperature of the bentonite directly in contact with a canister of spent fuel will be about 130°C, somewhat lower than values calculated previously (Nagra 2002c). Although it is considered unlikely that alteration processes could affect the plasticity or swelling pressure of the bentonite buffer except close to the SF/HLW canister surface, due to its importance further work is being done in this area to investigate the possibilities to allow for higher heat output. It is also noted that buffer temperatures could be lowered somewhat by increasing the cooling time before waste emplacement.

Studies of the hydration of bentonite pellets at 20°C and 90°C have shown that the pelletised material is indistinguishable from compacted block material of the same density in terms of swelling capacity and hydraulic conductivity (Karnland et al. 2007).

Focus of work – Laboratory and field investigations of the changes in swelling, plasticity and hydraulic properties of thermally altered bentonite will be performed. The work will focus on the behaviour of low moisture content, dense bentonite granules, which are expected to constitute the dominant fraction of the backfill. Some of the studies are being done in cooperation with SKB in the context of the LOT[67] experiment, which covers the temperature range from 90 to 150°C and the ABM[68] experiment, which evaluates various bentonites at temperatures up to 130°C (SKB 2008). Additional laboratory investigations are being performed at ETH at temperatures up to 150°C including partially saturated conditions, to determine how the swelling and hydraulic properties and mineralogy are affected by the repository heating transient. Coupled thermo-hydro-mechanical (THM) calculations of near-field evolution after canister emplacement will be performed to aid in planning the studies, in coordination with studies of the resaturation phase and of EDZ evolution. The laboratory studies will be combined with a synthesis of information from natural analogue studies.

Fe-bentonite interactions

Objectives of work – One of the issues regarding the long-term stability and integrity of the bentonite buffer is the effect of possible interaction between bentonite and steel canisters. There is a possibility that Fe(II) released as a result of dissolution of corrosion products might affect the swelling, ion exchange and retention properties of the bentonite. The studies being pursued

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[67] LOT: Long-term test of buffer materials (experiment in the Äspö rock laboratory).

[68] ABM: Alternative buffer materials (Äspö experiment).

will provide the basis for understanding the mechanism of the interactions and thus providing a basis for evaluating the safety-relevant impacts.

Status of work – Several recent studies of iron-clay interactions have shown that substantial uptake onto bentonite occurs during corrosion of steel under anaerobic conditions, but that Fe(II)-rich alteration products form very slowly and are difficult to identify (Carlson et al. 2006, Xia et al. 2005). Modelling studies have examined different approaches to assessing impacts on bentonite (Wersin et al. 2007, Savage et al. 2007). Nagra participated in a workshop organised by Posiva that was held in late 2007 with the objective of discussing potential international collaboration on iron–clay interactions. The workshop provided the basis for Nagra to define studies that will complement those being performed by other organisations.

Focus of work – The main focus of work for Nagra will be to study of the effects of adsorbed Fe(II) on retention of radionuclides and assessment of impacts on hydraulic and swelling properties. Collaboration on iron-clay interactions is being pursued in cooperative work involving PSI and ETH Zurich. The goal is to understand radionuclide retardation by bentonite under the influence of different concentrations of dissolved Fe(II), including the interaction between radionuclides and redox-active Fe(II) and the stability of different clay minerals in Fe(II)-rich environments. An international collaboration between Posiva and PSI allows an informal exchange of information and results. A natural analogue study on London clay proposed by the British Geological Survey (BGS) is also being considered.

Bentonite consolidation and creep

Objectives of work – To evaluate the coupled processed during bentonite saturation and swelling and investigate the potential of the buffer material to avoid sinking of the canister and to mechanically stabilise the emplacement tunnels. Buffer material consisting of bentonite or bentonite / sand mixtures may become ductile after saturation. Depending on material emplacement density, some creep of the bentonite may occur, which might affect the behaviour of the engineered barrier. In addition, compaction of the dry or saturated granular bentonite due to creep processes of the host rock could affect the evolution of the EDZ.

Status of work – In-situ measurements of canister movement and bentonite compaction were carried out within the EB experiment at Mont Terri (Mayor et al. 2007a). The saturation of the buffer material is still ongoing and the monitoring of convergence, bentonite swelling pressure and canister movement is still active.

Börgesson & Hernelind (2006) have conducted numerical modelling of the canister sinking process for the KBS-3V concept and concluded that even for relatively low bentonite densities the canister sinking is limited to a few centimetres even for very long time scales.

Focus of work – It is planned to continue the EB experiment at Mont Terri as part of the project PEBS which will be re-submitted within the EU 7th Framework Programme. The careful excavation of the experimental site and laboratory experiments on the saturated bentonite samples will allow a better evaluation of the rheology of the material. Modelling of the time-dependent (creep) behaviour of the material will be carried out to verify the results from Börgesson & Hernelind (2006) for the Nagra emplacement concept.

Evaluation of interactions of cementitious materials with compacted clay-containing materials

Objectives of work – To improve the understanding of the impacts of cementitious materials on the properties and evolution of compacted clay materials (Opalinus Clay, other sedimentary host rocks, bentonite and bentonite-sand mixtures). There are several applications in which cementitious materials may come into contact with bentonite-based sealing materials and/or Opalinus Clay. These include:

- possible use of low-pH shotcrete liner for HLW emplacement tunnels (see Section 6.5.3.3.3)
- emplacement of gas permeable sand/bentonite seals at the entrances to L/ILW emplacement caverns (see Section 6.5.3.3.5)
- use of conventional concretes as liners and cementitious mortar materials in L/ILW emplacement caverns
- use of conventional shotcrete liners in main access and operations tunnels

Alkaline porewaters from cementitious materials are in general detrimental towards clay minerals and alteration may thus occur, affecting in particular the safety-relevant hydraulic and swelling properties. The significance of the interactions varies depending on the composition of the material used and its application.

Status of work – Considerable modelling and experimental work has been done on interactions between conventional concretes and clay, but there are acknowledged to be significant uncertainties. In relation to conventional concretes interacting with Opalinus Clay, assessment studies suggest that an alkaline plume will penetrate, at most, a few metres into Opalinus Clay, because of slow transport in the rock (Nagra 2002c). The extent of alteration may be considerably less, but the kinetics of the dissolution and precipitation processes remain quite uncertain. A recent comprehensive review in this area is provided in the ECOCLAY II[69] final report (ANDRA 2005b).

In relation to the interaction between low pH shotcrete and bentonite, very little work has been done. Based on the few studies, the expectation is that the pH is not high enough to cause substantial alteration of bentonite.

Focus of work – The studies of interaction of low pH shotcrete and bentonite are presently being defined. As a first step, the specific pH value in porewater in low pH shotcrete is being determined. Methods to study the interaction will then be developed. In relation to conventional concretes, laboratory experiments will be carried out on Opalinus Clay using portlandite-buffered water (pH 12.2). Earlier laboratory experiments on Opalinus Clay were mainly carried out with young cement water (pH 13.5). At the Mont Terri URL, a long-term (up to 20 years) low maintenance experiment is being performed using both conventional and low pH concretes. Numerical modelling of the findings of all experiments will be carried out as appropriate. Other experiments are under development at PSI.

[69] ECOCLAY II: Effects of cement on clay barrier performance, phase II (EU project).

6.5.4.2.3 Gas/water transport through bentonite barriers

Objectives of work – To improve the understanding and the modelling capabilities for transport of gas and water through bentonite materials used as backfill around canisters that will produce gas due to corrosion (steel canisters or copper canisters with iron structural inserts). Bentonite/ sand mixtures may also be used as sealing materials for emplacement caverns for L/ILW containers, to provide enhanced gas transport from the system (see Section 6.5.3.3.5). The fluid flow and gas transport properties of these backfills/sealing materials need to be quantified to analyse barrier performance and to evaluate maximum gas pressures in the near-field and to quantify gas flow rates from the disposal system.

Status of work – Water flow through bentonites and bentonite/sand mixtures has been studied for many years and corresponding permeabilities are well known. Work on gas transport has been done in the context of the GAMBIT programme of work (Hoch et al. 2004, Rodwell 2005) and is ongoing within the EBS Task Force of SKB's Äspö Laboratory (SKB 2008), which deals with modelling gas transport through bentonite (Senger et al. 2009). The experiments on gas transport through dense bentonite and the associated models do not yet provide a basis for convincingly determining whether micro-pathway dilation or two-phase flow is responsible for gas transport. In the case of sand/bentonite mixtures with low bentonite content, two-phase flow has been demonstrated. For the L/ILW repository concept, a compilation of two-phase flow properties for sand/bentonite mixtures can be found in Nagra (2008g).

Focus of work – The work programme includes (i) laboratory studies for the investigation of combined solute/gas transport processes in bentonite and sand/bentonite mixtures, including phenomenological studies and material characterisation work, (ii) improvement of modelling tools for gas transport in heterogeneous buffer materials, (iii) active participation in international near-field research programmes.

Nagra will participate with comprehensive laboratory and in-situ experiments in the projects FORGE (EU 7th Framework Programme) and PEBS (proposed EU project) and is involved in the ongoing Äspö EBS Task Force. Further laboratory studies[70] are planned or have been initiated already. Modelling activities concentrate on the development of upscaling techniques for gas and solute transport.

6.5.4.2.4 Development of coupled THMC modelling capability

Objectives of work – To improve the quantitative coupled THMC modelling capabilities that can be used to enhance understanding of the interaction of the different processes in the near-field in the initial phase after waste emplacement and their impacts on the safety functions of the engineered barriers and in the host rock in the direct vicinity of the emplacement rooms. THMC processes occurring in the transient thermal phase of the HLW repository are not expected to have a direct impact on the retention characteristics of the various barriers (the processes mainly occur during the period when SF and HLW canisters are intact). Nevertheless, an understanding of these processes is important in demonstrating overall system understanding in support of a safety case.

Status of work – The need for development of improved coupled THMC modelling capabilities for near-field processes was recognised during development of Project Entsorgungsnachweis, when preliminary studies were performed on the behaviour of the bentonite buffer during

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[70] Project LabPerm: new initiative on water flow and gas transport processes in Opalinus Clay and sand/bentonite mixtures.

resaturation. Nonetheless, limited data was available regarding important coupling parameters. A review of the THMC processes in the near-field of a SF/HLW disposal system was accomplished in the EU NF-PRO project (Huertas et al. 2008). Furthermore, comprehensive synthesis reports on two heater experiments and an EBS experiment have been completed as part of the Mont Terri Research programme (Göbel et al. 2007, Wileveau & Rothfuchs 2007, Mayor et al. 2007a). Comprehensive thermo-hydraulic modelling activities have been carried out to explore the bentonite resaturation transient for SF canisters (Senger 2006, Senger & Ewing 2008).

Focus of work – The work programme includes (i) laboratory programmes for the derivation of THM constitutive laws of granular bentonite, (ii) large-scale heater tests for the evaluation of existing THM near-field model capabilities, (iii) model development and (iv) active participation in international near-field research programmes.

A laboratory programme on THM constitutive laws for Opalinus Clay samples from the Mont Terri URL is being performed in the THM-EDZ and THM-LabPerm projects. Work is also being performed on the thermal conductivity of granular bentonite and bentonite/sand mixtures at ETH Zurich. A small-scale in-situ heater experiment has been started recently at the Mont Terri URL (TIMODAZ, EU 7th Framework Programme) and three new experiments are planned in near future, comprising a 1:2 scale experiment in the VE tunnel, the dismantling of the EB experiment (PEBS proposal, EU 7th Framework Programme) and a new real-scale heater test in the Mont Terri URL. Long-term monitoring of the FEBEX-e[71] experiment, a full-scale heater experiment installed at the Grimsel test site in 1996 will be continued until at least 2012 and results from the study will be available for model testing.

Model development concentrates on the following aspects: (i) development of THM material laws for Opalinus Clay and bentonite (THM-Bent[72]; THM-Task Forces), (ii) development of systematic process abstraction methods for safety assessment (THM-Gas-MOD) and (iii) non-isothermal insight models on the evolution of pore pressure and stress around the backfilled tunnels of a SF/HLW disposal system (participation in SKB's EBS Task Force; SKB 2008). Further modelling activities have been started as part of the TIMODAZ project (EU 7th Framework Programme).

6.5.5 Development of the concept for repository monitoring

Objectives of work – To develop a concept, and eventually detailed methods and techniques, for reliable monitoring of a repository. The monitoring covers all phases of repository implementation, including site investigation, construction of access tunnels and shafts, construction and operation of the rock laboratory (test facility), construction and operation of the pilot and main facility and the observation period (post-waste emplacement monitoring). A key feature of the monitoring concept is the monitoring of a pilot facility containing a representative amount of waste, as defined by EKRA (FOE 2000).

Monitoring may provide repository implementers, expert reviewers (e.g. safety authorities) and lay (e.g. public) stakeholders with in-situ data over the full life cycle of the repository project. Such data may be used to confirm the predicted initial repository evolution, contribute to operational safety and provide input for the staged repository implementation process, the operation

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71 FEBEX-e: Full-scale Engineered Barriers Experiment for a Deep Geological Repository for High-level Waste in Crystalline Rock – Extension (Grimsel Test Site experiment).

72 THM-Bent: Characterisation and constitutive modelling of the behaviour of granular bentonite during Thermo-Hydro-Mechanical Processes (Nagra RD&D project).

and/or closure activities. Comparison of the monitoring results with prior performance assessments (i.e. performance confirmation) and process models may contribute to increased transparency and stakeholder confidence regarding the disposal process. Monitoring should also provide the opportunity to detect any early unexpected evolution of the system.

The monitoring concept to be developed for the general licence application will concentrate on the monitoring in the pilot facility and monitoring during the observation period.

Status of work – Basic considerations regarding monitoring have been developed in the context of previous repository feasibility studies (e.g. general licence application Wellenberg). An international monitoring project (MoDeRn[73]) has been proposed to the EU within the 7th Framework Programme and the contract negotiations are close to being finished. This project includes the development of monitoring concepts, equipment and methods (e.g. wireless monitoring and non-intrusive monitoring techniques).

Monitoring equipment has been successfully tested in a large number of in-situ experiments in underground laboratories. Some of the experiments have been dismantled and the sensors have been recalibrated to allow evaluating the reliability of such sensors over decades (e.g. FEBEX).

Dedicated monitoring projects are active at the Grimsel Test Site (TEM[74] experiment; Marelli et al. 2008) and Mont Terri (GP-A[75]; Manukyan et al. 2008) to test wireless and non-intrusive monitoring techniques.

Focus of work – Potential monitoring concepts including a concept for using a pilot facility will be evaluated within the EC project MoDeRn. These basic concepts will be further developed to provide a comprehensive monitoring concept for the general licence applications. The development of the monitoring concept will also include the lay-out of the pilot facility.

Technological developments of monitoring equipment will be done within the MoDeRn project and, if possible, within other bi- or multi-lateral projects. The close interaction with partner organisations, which are more advanced in their disposal projects, will allow learning from their experience.

The planned 1:1 emplacement demonstration project at Mont Terri will have a significant monitoring programme and will provide valuable information, including the evaluation of adequate equipment and techniques.

Baseline monitoring will start with the detailed site investigations that will begin after granting of the general licence and will be intensified before construction work (tunnelling, shaft construction) begins. A network of piezometer boreholes and deep boreholes equipped with long-term monitoring systems will be established and water samples from water sources and/or groundwater will be analysed in specified time intervals. Meteorological measurements and a radiological monitoring programme will be set up according to the specifications of the authorities.

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73 MoDeRn: Monitoring Developments for safe Repository operation and staged closure (EU project proposal).

74 TEM: Test and Evaluation of Monitoring Techniques (Grimsel Test Site experiment).

75 GP-A: Hydraulic and gas permeability (Mont Terri experiment).

6.5.6 Other topics

There are additional topics that require development regarding concepts and approaches, but that are not considered RD&D issues requiring scientific or engineering work and are thus not discussed in the present report. These include the development of suitable methods for long-term markers for repositories and the need for long-term archiving of information regarding the repository and its contents. Both are requirements of the Nuclear Energy Law (KEG 2003) and work is proceeding on these issues.

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Appendix 1 Summary of the documentation needed to meet the Swiss legal requirements related to the implementation of geological repositories for radioactive wastes

Authority decision	**Documentation needed**	**Source of requirement**
Sectoral Plan – Stage 1 – Selection of geologically suitable regions	Reports including: Allocation of waste to the geological repositories Derived requirements for the geology (based on generic safety evaluation) Proposal of geological siting regions, including justification Basis for the recording of the land use planning situation	Concept SGT
Sectoral Plan – Stage 2 – Selection of at least two sites for the L/ILW- and HLW-repository	Report (documents and supports site selection). Includes preliminary safety assessments and assessment of land use planning and environmental issues	Concept SGT
Licence for geological investigations on 2 sites selected during previous phase (Stage 2)	a. Investigation programme b. Geological report c. Report on the potential impacts of the investigations on the geological conditions and the environment d. General maps and plans e. Indication of desired validity of the licence	KEV 58
Sectoral Plan – Stage 3 – Site selection	a. Report supporting the selection of the respective sites for LLW and HLW b. Report on compliance with land use planning requirements Both reports are also part of the general licence application	Concept SGT

Authority decision	Documentation needed	Source of requirement
General licence	a. Safety report and security report (incl. site charateristics, purpose and outline of project, anticipated exposure to radiation in the vicinity of the facility, details regarding staff and organisational structure, indication of long-term safety) b. Environmental impact report (EIA – Level 1) c. Report on compliance with land use planning requirements d. Concept for the monitoring period and closure of the facility e. Additional reports including: Comparison of available options related to the safety of the deep geological repository, evaluation of the decisive properties for the selection of the site, cost estimate	a, c – d: KEV 23 b: USG 9, UVPV 6 and Appendix, Chapter 4 e: KEV 62
Licence for an Underground Research Facility (geological investigations)	a. Investigation programme b. Geological report c. Report on the potential impacts of the investigations on the geological conditions and the environment d. General maps and plans e. Indication of desired validity of the licence	KEV 58
Construction licence	a. Facility concept / Layout concept according to KEG 7 through 12 b. Environmental impact report (EIA – Level 2) c. Report on compliance with land use planning requirements d. Quality management programme for the project and construction stages e. Emergency protection concept f. Project for the monitoring period and plan for closure of the facility g. Report on compliance of the project with the general licence requirements	a – g: KEV 24-2 b: USG 9, UVPV Art. 6 and Appendix, Chapter 4
Operating licence	a. Organisational and technical documentation b. Required documents for the operating licence c. Evidence of insurance cover d. Report on compliance of the facility with the requirements of the general licence and the construction licence e. Safety report and security report	a – d: KEV 28-1 e: KEV, Appendix 3

Authority decision	**Documentation needed**	**Source of requirement**
Preparation of monitoring phase	Updated project for the monitoring phase: a. Planned measures for monitoring the repository after emplacement of the waste has been completed b. Proposed duration of the monitoring period	KEV 68-1
Licensing for closure of repository	Closure project with reports addressing the following: a. backfilling and sealing of the accesses to the disposal areas b. modifications needed to ensure long-term safety of pilot repository c. backfilling and sealing the accesses to the repository d. assurance of long-term safety	KEV 69-2
Periodic updates	Updated Waste Disposal Programme Reports on cost estimates for decommissioning and waste disposal	KEV 52-2 SEFV 4

Sources:

Concept SGT: Sachplan geologische Tiefenlager, Konzeptteil, 2nd April 2008

KEV: Nuclear Energy Ordinance of 10th December 2004 (Status as of 1st February 2005). SR 732.11

USG: Environment Protection Act of 7th October 1983 (Status as of 4th July 2006). SR 814.01

UVPV: Environmental Impact Assessment Ordinance of 19th October 1988 (Status as of 9th January 2007). SR 814.011

Appendix 2 List of acronyms

ABM	Alternative Buffer Material (Äspö experiment)
ACTINET	European Network for Actinide Sciences
ANDRA	National Radioactive Waste Management Agency, France (Agence nationale pour la gestion des déchets radioactifs)
BGS	British Geological Survey, United Kingdom
BIOPROTA	International Forum for Biosphere Modelling
BWR	Boiling Water Reactor
BZL	Storage facility operated by PSI for wastes from medicine, industry and research (Bundeszwischenlager)
CI	Cement Clay Interaction (Mont Terri experiment)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CLAYTRAC	OECD / NEA Clay Club Project
DETEC	Federal Department of the Environment, Transport, Energy and Communications
DI-A	Long-term Diffusion (Mont Terri experiment)
DI-B	Hydrogeochemistry and Transport Mechanisms (Mont Terri experiments)
DR	Radionuclide Diffusion and Retention (Mont Terri experiment)
DS	Stress determination and monitoring (Mont Terri experiment)
EB	Engineered Barriers (Mont Terri experiment and EU project)
EBS	Engineered Barrier System
EBS Task Force	International Working Group for Modelling of Coupled THM Processes in Engineered Barriers (Äspö)
ECOCLAY II	Effects of cement on clay barrier performance, phase II (EU project)
EDZ	Excavation Disturbed Zone
EKRA	An expert group established by the Federal Department of the Environment, Transport, Energy and Communication to develop radioactive waste disposal concepts (Expertengruppe Entsorgungskonzepte für radioaktive Abfälle)
EDL	Electrostatic double layers
EMPA	EMPA Materials Science and Technology, Dübendorf, Switzerland
EMRAS	Environmental Modelling for Radiation Safety (IAEA-Programme)
ENRESA	Empresa Nacional de Residuos Radiactivos S.A., Spain
ENSI	Swiss Federal Nuclear Safety Inspectorate (Eidgenössisches Nuklearsicherheitsinspektorat), before 1.1.2009: HSK
EPFL	Swiss Federal Institute of Technology, Lausanne (Ecole polytechnique fédérale de Lausanne)
ESDRED	Engineering Studies and Demonstration of Repository Designs (EU project)
ETH	Swiss Federal Institute of Technology, Zurich (Eidgenössische Technische Hochschule Zürich)

EU	European Union
EZ-A	EDZ cut-off (Mont Terri experiment)
FEBEX-e	Full-scale Engineered Barriers Experiment for a Deep Geological Repository for High-level Waste in Crystalline Rock – Extension (Grimsel Test Site experiment)
FEP	Features, events and processes
FOE	Swiss Federal Office of Energy
FORGE	Fate of Repository Gases (EU project)
FUNMIG	FUNdamental processes in radionuclide MIGration (EU project)
GAMBIT Club	Consortium of waste management agencies set up to support a programme of work on the development of a computational model of gas migration in highly compacted water-saturated bentonite
Gas-MOD	Development of geoscientific modelling capabilities related to combined water/gas transport processes (Nagra RD&D project)
GD	Analysis of geochemical data (Mont Terri experiment)
GP-A	Hydraulic and Gas Permeability (Mont Terri experiment)
GTS	Grimsel Test Site
HA	Hydrogeological Analyses (Mont Terri experiment)
HADES	Underground Research Facility in Mol, Belgium, operated by ONDRAF / NIRAS
HLW	High-level waste
HG-A	Gas paths through host rocks and along seals (Mont Terri experiment)
HG-C	Long-term gas migration in undisturbed argillaceous formations (Mont Terri experiment)
HG-D	Reactive gas transport in argillaceous formations; Mont Terri experiment
HM processes	Hydromechanical processes
HSK	Nuclear Safety Inspectorate (Hauptabteilung für die Sicherheit der Kernanlagen), from 1.1.2009: ENSI)
HT	Hydrogen Transfer (Mont Terri experiment)
IAEA	International Atomic Energy Agency
ICONNECT	Integrated CONtinuum and NEtwork approach to groundwater flow and Contaminant Transport
ICRP	International Commission on Radiation Protection
ILW	Intermediate-level waste
INTERREG III	European Community initiative aiming at stimulating interregional cooperation in the EU between 2000 and 2006, it was financed under the European Regional Development Fund (ERDF)
IRF	Instant Release Fraction
IRRC	Integrated Radionuclide Release Code
IRSN	Institut de radioprotection et de sûreté nucléaire, Frankreich
IRT	International Review Team of OECD Nuclear Energy Agency
JAEA	Japan Atomic Energy Agency

KNE	Commission on Nuclear Waste Management (Kommission Nukleare Entsorgung)
KSA	Federal Commission for Nuclear Safety (Kommission für die Sicherheit von Kernanlagen)
LES / PSI	Laboratory for Waste Management, Paul Scherrer Institute
LLW	Low-level waste
LOT	Long Term Test of Buffer Material (Äspö experiment)
MB	Mine-by test (Mont Terri experiment)
MS	Mass Spectroscopy
MT	Mont Terri
MICADO	Model uncertainty for the mechanism of dissolution of spent fuel in a nuclear waste repository (EU project)
MIR	Medicine, Industry and Research
MIRAM	Model Waste and Materials Inventory
MoDeRn	Monitoring Developments for safe Repository operation and staged closure (EU project proposal)
MOX	Mixed Oxide fuel
NEA	Nuclear Energy Agency of the OECD
NF-PRO	Understanding and physical and numerical modelling of the key processes in the near-field and their coupling for different host rocks and repository strategies (EU project)
ONDRAF / NIRAS	Organisme national des déchets radioactifs et des matières fissiles, Belgiun
PAMINA	Performance Assessment Methodologies to Guide the Development of the Safety Case (EU project)
PC	Porewater Chemistry Experiment (Mont Terri experiment)
PC-C	Gas porewater equilibrium (Mont Terri experiment)
PEBS	Long-term performance of Engineered Barrier Systems (EU project proposal)
Posiva	Posiva Oy, Finland
PSA	Probabilistic Safety Assessment
PSI	Paul Scherrer Institute
PWR	Pressurized Water Reactor
QMS	Quality Management System
RECOSY	Investigations of Redox Controlling systems (EU project)
RWTH	Rheinisch-Westfälische Technische Hochschule Aachen, Germany
SB	Self-sealing barriers of clay-sand mixtures (Mont Terri experiment)
SELFRAC	Fractures and self-healing within the excavation-disturbed zone in clays (Mont Terri experiment and EU project)
SF	Spent fuel
SFS	Spent Fuel Stability (EU project)

SGT	Sectoral Plan "Deep geological repositories" (Sachplan geologische Tiefenlager)
SHARC	Shale Research Centre of CSIRO, the SHARC Consortium is a joint industry project
SKB	Svensk Kärnbränslehantering AB, Sweden
TDB	Thermochemical Database Project of the OECD / NEA
TEM	Test and Evaluation of Monitoring Techniques (Grimsel Test Site experiment)
THM-Bent	Characterisation and constitutive modelling of the behaviour of granular bentonite during Thermo-Hydro-Mechanical Processes (Nagra RD&D project)
THMC Processes	Coupled Thermo-Hydromechanical and Chemical Processes
THM-EDZ	Development of THM-modelling capabilities for simulating the EDZ evolution before and after repository closure (Nagra RD&D project)
THM-LabPerm	Laboratory programme on the investigation of gas transport and pathway dilation process in Opalinus Clay and in buffer materials (Nagra RD&D project)
THM Task Force	SKB Task Force on engineered barriers, associated with the Äspö Hard Rock Laboratory
TIMODAZ	Thermal impact on the damaged zone around a radioactive waste disposal in clay host rocks (EU project)
TSM	Thermodynamic Surface Models
UPC	Universitat Politècnica de Catalunya, Spain
URL	Underground Research Laboratory
USM	Lower Freshwater Molasse (Untere Süsswassermolasse)
VE	Ventilation Test (Mont Terri experiment)
XAS	X-ray Absorption Spectroscopy
ZWIBEZ	Waste storage facility located at Beznau nuclear power plant
ZWILAG	Centralised storage facility located in Würenlingen, operational since 2002